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An Integrated Bi-directional Automotive Charging System With Controller

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AN INTEGRATED BI-DIRECTIONAL AUTOMOTIVE CHARGING SYSTEM WITH CONTROLLER

By

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ABSTRACT

Electric vehicles and Hybrid electric vehicles are fetching the attraction of the consumers because of the increasing fuel cost. The growing number of EVs/ HEVs has given a new area to think of since these vehicles can be a part of a renewable energy system. The main idea is to deliver the stored energy of an electric/ hybrid vehicle to the power grid. EVs which are out in the market till date are not capable of transferring the stored energy to the grid because of the power electronics design they have. To implement the new idea of transferring energy back to grid, changes in the installed design is required.

A comprehensive study of the various models of the converter system has been discussed in this paper. In this research a design of the integrated bi-directional converter has been proposed. A controller has been introduced to make the converter works more efficiently. Model simulation results with graphical interpretation have been given to validate the design.

To

My Parents: Golam Mostafa Khan and Hasina Mostafa

&

My Beautiful Wife: Sabrina Manzur

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I would like to thank almighty Allah for making me able to finish my degree and achieve my success by the completion of this degree. Without His wish and blessings, I do not think it would be possible for me to even think of it. In the beginning of the degree, my only reliance was Allah and I sought all type of help from him. Whenever I faced any mental, financial or academic problem during my degree, He was there to show me the path to proceed. Today, at the verge of finishing my degree, I would like to thank Him for being with me as my guide.

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NOMENCLATURE

f	= Operating Frequency
P	= Conversion Power
L_o	= Inductance
V_{dc}	= DC Link Voltage
V_b	= Battery Voltage
v_{grid}	= Instantaneous Grid Voltage
V_{grid}	= Root Mean Square of Grid Voltage
v_{conv}	= Instantaneous Converter Voltage
V_{conv}	= Root Mean Square of Converter Voltage
δ	= Angle between the Grid Voltage and Converted Voltage
m	= Modulation Index
i_{grid}	= Grid Current
θ	= Angle between Grid Current and Converted Voltage
f_{max}	= Maximum Switching Frequency
L_C	= Coupling Inductance
H	= Difference between the Upper and Lower Hysteresis Band
v_{cap}	= Instantaneous Voltage of the Capacitor
i_{cap}	= Instantaneous Current of the Capacitor
i_{dc}	= DC Current Output
i_{conv}	= Converter Current
T_s	= Total Time Period
t_{on}	= Switch On Time
t_{off}	= Switch Off Time
D	= Duty Ratio
V_o	= Output Voltage
V_i	= Input Voltage
I_b	= Battery Current
I_o	= Output Current
I_{ref}	= Reference Current

$V_T(n)$	= Output of PI Controller at *nth* instant of time
K_p	= Proportional Gain
K_i	= Integral Gain
$v_{triangular}$	= Carrier Signal Triangular Wave
$v_{control}$	= Control Signal Sinusoidal Wave
V_{ref}	= Reference Voltage
V_{error}	= Error Voltage of the PI Controller
I_{error}	= Error Current of the PI Controller
I_{grid}	= Grid Current
I_T	= Output of PI Controller at *nth* instant of time
I_K	= Difference between I_{grid} and I_T
V_K	= Control Signal of the Second Controller
K	= Gain

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Environmental and economic problems have led us to think of generating power on-site. Now a day the flexibility of smaller power generating systems has opened a new area of research. Solar cells, wind turbines etc. are well known recent days for generating renewable energy. Micro-grids are the new concept in this arena for storing energy as well as generate power from naturally available renewable sources. In spite of being costly and complex structural design, the main advantage of them is the flexibility they can provide to the consumers. Here comes the concept of Vehicle to Grid technology where the vehicle will be functioning as a micro-grid. Electric Vehicles (EV) and Plug-in Hybrid Vehicles (PHEV) are the main concern for vehicle to grid (V2G) technology as in general vehicles are parked approximately 15 hours per day and give the opportunity to use them as a power generation source.

The main idea for V2G technology is to use the vehicle as a generation unit. The vehicle will provide power to the grid when it is parked or plugged in. For that reason, the EV or PHEV should be equipped with bidirectional converter with an additional powerful battery pack. With the help of the bidirectional converter, two ways energy flow can be operated; flow from the grid to the vehicle and flow from the vehicle to the grid. To save more, the vehicle battery pack can be charged at night; and the battery pack can be discharged when the power demand is high [23], [24].

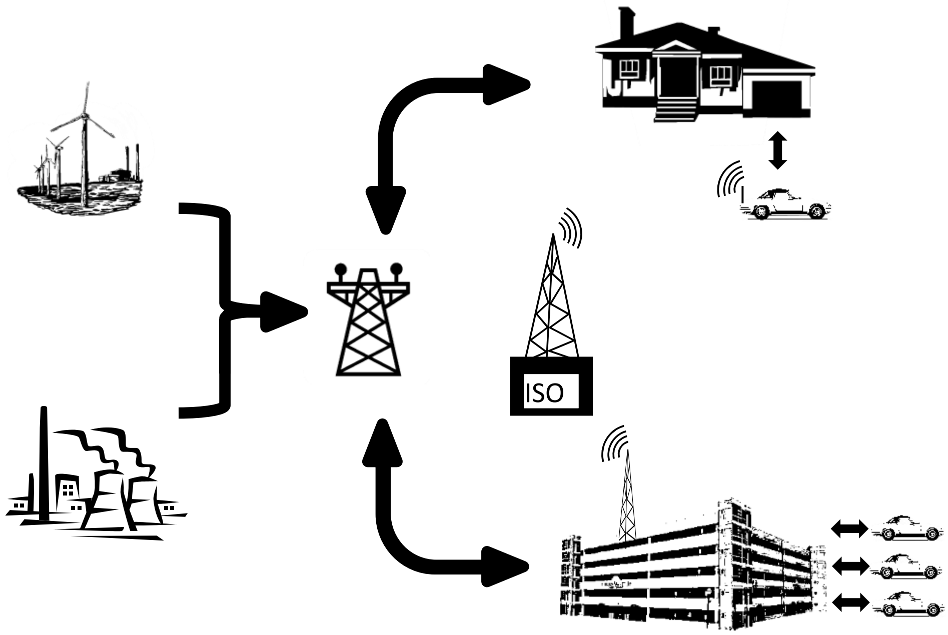

Fig 1.1: Implementation of Vehicle to Grid technology [1]

Fig. 1.1 shows the basic concept of the V2G technology. Electric vehicles or Plug-in Hybrid Vehicles can be connected either to the house or to the utility for performing V2G operation. Charging and discharging of the battery pack of the vehicle can be determined by centralized operator Independent System Operator (ISO). The operator can be used to make the balance between production and consumption of power. Matching the frequency with the grid, keeping power factor unity etc. can be done by the central operator [1].

The battery pack should not be connected to the dc bus directly. In the case of direct connection, the charging and discharging current cannot be controlled. If load changes significantly, rush current can destroy the whole battery pack. This is the reason of using a bidirectional converter. It needs to be introduced between the dc bus and discharging current [2]. The converter should be bidirectional so that it can convert the dc voltage to ac and ac voltage to dc.

A dc-ac converter is a device that converts direct current to alternating current. Switch mode dc-dc converter topology has been used for dc-ac converter in recent years. Several advantages of this includes operating at a high frequency, cost effectiveness as the capacitor in the circuit can be a smaller and less expensive one [3]. For integrating the dc-dc converter with the dc-ac converter, the traditional topology does face some problem such as, the switching time, the bi-directional behaviour etc. A sample topology for the V2G system has been shown below:

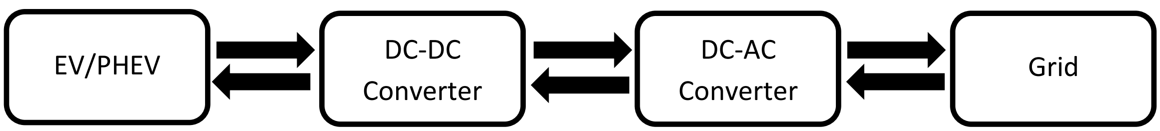

Fig 1.2: Block diagram of Vehicle to Grid technology

1.2 RESEARCH OBJECTIVES

Electric vehicle technology has become a popular technology as this has some crucial advantages compare to the conventional vehicles. Fuel economy and lower emission rate are among of those. This research is focused on an overview of how electric vehicles and plug-in hybrid vehicles can be used as distributed generators. An integrated bidirectional dc-dc converter and dc-ac converter has been proposed here for electric vehicles and plug-in hybrid vehicles. The proposed converter is able to function as an interface between the vehicle and the grid. By this method, the vehicle will be able to transfer power back to the grid when the owner needs that power.

My research is focused on modeling the bidirectional converters that is capable of power flow in both ways, from grid to the battery of the vehicle for charging, and from battery to the grid side as well. In this thesis, the specific areas which complete the whole system are:

- Bi-directional DC-DC converter
- Bi-directional DC-AC converter
- Controller

1.3 PROBLEMS WITH EXISTING DESIGNS

There are several design issues surrounding the EV and PHEV battery charger. First of all, most of the chargers which exist in the market are not bidirectional chargers. The bidirectional capability is needed for transmitting power from vehicle to the grid. Converters with the bidirectional property have been proposed in many papers. Different topologies have been introduced by the authors. Some of the topologies have high number of switches, some of them have harmonics problem.

High number of switches is not good for V2G application. High number of switches may lead the design to more conduction loss. The amount of power generation from vehicle to grid side is not very high, so for switching less power loss is required.

The input current which is going to the grid side should have fewer harmonics. The IEEE 519 standard allows an amount of 5% of total harmonics distortion to inject into the grid. Any amount that is more than 5% is not acceptable as this may pollute the grid current.

Bi-directional ability is another issue with the existing designs. In the proposed designs, lots of them do not have the bi-directional feature that can successfully operate the power flow from vehicle side to the grid side.

1.4 MAIN POINTS OF MY WORK

The automotive industry is going through a major restructuring. A new generation of hybrid vehicles has been introduced names Plug-in Hybrid vehicles. It is becoming more available and popular day by day. The numbers has increased rapidly in recent days. There comes the issue of charging a large number of vehicles whether the grid can sustain the increased load or not. Although these vehicles appear to pose a large liability to the grid, with proper execution, they can be a larger asset. The grid can have a great benefit from these vehicles as these vehicles can store or release energy at the appropriate times. Enabling PHEVs to fulfill this function will require a bi-directional interface between the grid and each vehicle [5]. This bi-directional charger must have the capability to charge a PHEV's battery pack while producing minimal current harmonics and also have the ability to return energy back to the grid in accordance with regulations. My research work includes the review of some of the power electronic topologies of bi-directional AC-DC and DC-DC converters that fulfill these requirements of vehicle to grid connectivity and then design a whole system for combining two topologies to form a bidirectional charger.

1.5 THESIS OUTLINE

The thesis has been organized as the 1st chapter has started with the introduction and overview of the vehicle to grid idea. Some problems of the recent designs have been pointed out. And finally the main objective of this research is discussed with the explanation of the main points of this work.

The 2nd chapter mainly consists of description of electric and hybrid vehicles. Different types and topologies of hybrid electric vehicles have been discussed. Literature study and the outcome of that study have been given in this chapter.

The 3rd chapter of the thesis is about the elaboration of vehicle to grid technology. Why is the technology necessary, the advantages and disadvantages have been discussed. Different charger types, charging schemes, required time and an outline has been given. The issues have been pointed in order to integrate the vehicle system with the grid.

In the 4th chapter of the thesis two converter models have been proposed. One of them is a bi-directional dc-dc converter and another one is a bi-directional dc-ac converter. A full integrated converter topology has been introduced in this chapter.

The 5th chapter of the thesis consists of the design of the controller to control the converters. A brief description has given on how this controller works with the converters.

The 6th chapter of the thesis is on simulation and results. MATLAB/Simulink software has been used to design and simulate the converter models. Results with graphs have been discussed in this chapter.

The 7th chapter is the conclusion. It also consists of the main contributions of this research and future scopes on this research.

CHAPTER 2

LITERATURE REVIEW

2.1 ELECTRIC VEHICLES

An electric vehicle is the vehicle which uses electric motors for propulsion. A working topology of an EV has been shown in the Figure 2.1. It may include a battery pack for storing energy, an electric motor and a controller. The battery is a rechargeable battery which can be charged by a battery charging unit that is installed in the residence. The controller can controls the power consumption by the vehicle and hence the speed of the vehicle. Regenerative braking is more desirable in the vehicle to regain the energy while braking. A controller with the ability of controlling the regenerative braking is known as four quadrant controller and without this ability, known as Two quadrant controller [4].

All of the electric vehicles have a fairly limited range and performance, but they are sufficient for the intended purpose. It is important to remember that the car is a very minor player in this field.

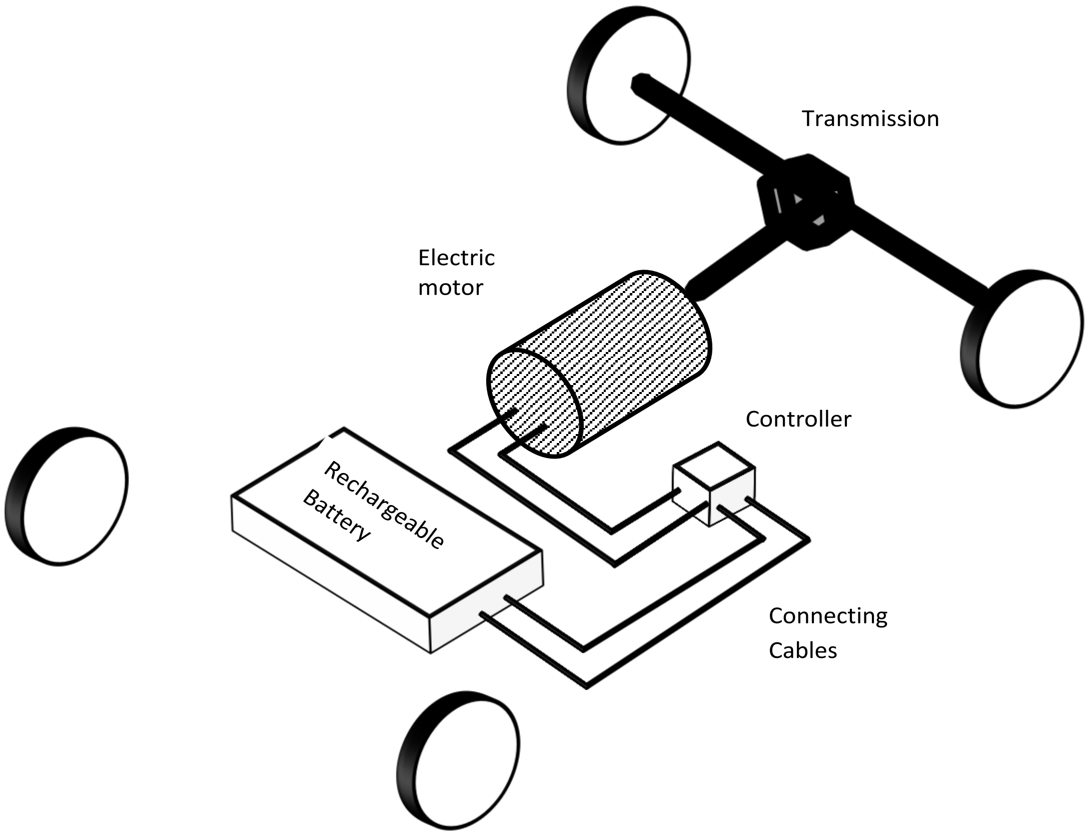

Fig 2.1: Rechargeable battery electric vehicle system [4]

2.2 PLUG-IN HYBRID VEHICLES

A plug-in hybrid vehicle is a type of vehicle which contains one or more rechargeable battery packs. The battery pack can be restored to fully charged status by connecting to an external power source. A PHEV has both the characteristics of a conventional hybrid vehicle and an all-electric vehicle. PHEV has the electric motor and an internal combustion engine like conventional hybrid vehicle; and a plug to connect to the power outlet like an all-electric vehicle. PHEV is known mainly for its larger all-electric range as compared to conventional gasoline-electric hybrids. Once the electric charge has been used, the combustion engine works as a backup.

A hybrid vehicle has two or more power sources, and there are a large number of possible variations. The most common types of hybrid vehicle combine an internal combustion engine with a battery and an electric motor and generator.

There are two basic arrangements for hybrid vehicles, the series hybrid and the parallel hybrid.

2.3 SERIES HYBRID VEHICLES

Series hybrid vehicles are driven by one or more electric motors in which power supplied from either the battery or from the combustion engine. In both cases, the driving force comes entirely from the electric motor. These types of vehicles are designed to be run mostly by the battery with an option of a petrol or diesel generator to recharge the battery when going on a long drive. The concept can be viewed as an electric transmission, with the battery storing reserve power until it is needed [11].

The series hybrid tends to be used only in specialist applications. For example, the diesel powered railway engine is nearly always a series hybrid, as are some ships. Some special all-terrain vehicles are series hybrid, with a separately controlled electric motor in each wheel. The main disadvantage of the series hybrid is that all the electrical energy must pass through both the generator and the motors. This considerably increases the cost of the system [4].

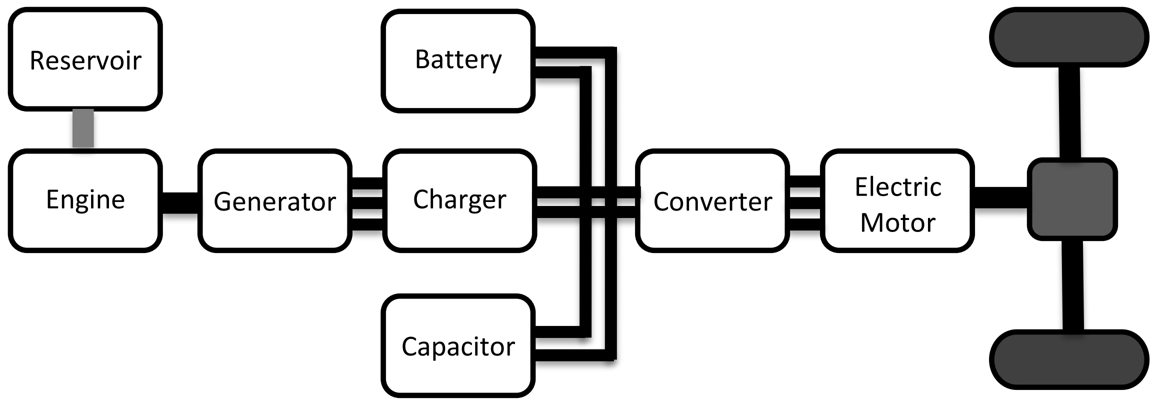

Fig 2.2: Series hybrid vehicle layout [11]

2.4 PARALLEL HYBRID VEHICLES

In the parallel hybrid system, the vehicle can be driven either by the internal combustion engine or by one or more electric motors. When the vehicle uses the IC engine, it works directly through a transmission system to the wheels. The vehicle might be driven by both the IC engine and the electric motor together.

The parallel hybrid system has scope for very wide application. In this concept, the electric machines can be much smaller and cheaper, as they do not have to convert all the energy.

In both the series and parallel hybrids, the battery can be recharged by the engine and generator while moving. An advantage in the hybrid vehicles is that the battery does not need to be as quite large as it is in electric vehicles. Both the series and parallel hybrids allow regenerative braking that is recharging while braking. The drive motor works as a generator and simultaneously slows down the vehicle and charge the battery [4].

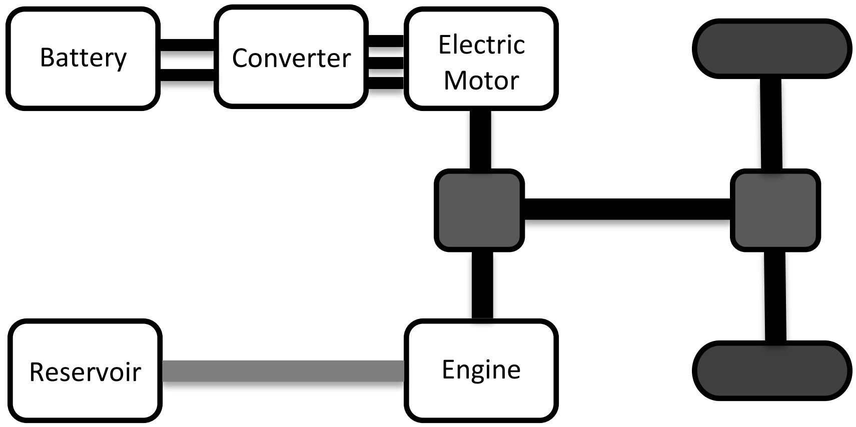

Fig 2.3: Parallel hybrid vehicle layout [11]

2.5 ADVANTAGES OF EV AND PHEV

Hybrid vehicles have the biggest advantage of being fuel economy by 20-40% compared to traditional vehicles. The cost savings in terms of fuel efficiency, electric vehicles are better than the hybrid vehicles as those can be recharged from the electricity grid and having no cost for fuel. Though the EVs and HEVs are expensive than the conventional vehicles now a day, but the initial cost for EVs and HEVs are decreasing day by day as the sales are increasing. And it will decrease even more in the long run that soon the purchase cost will be less than the traditional vehicles.

In addition, another advantage is that the cost is very much predictable to the consumers as the electricity price is quite stable rather than the fuel price. The fuel cost has increased a lot in recent years. And the price can go up anytime depending on the fluctuations caused by international pressures and disruption in oil supply.

Another advantage for the EVs and HEVs include a quiet ride with an increased convenience. As most of the houses and offices have been provided electricity, trip for refueling with gas can be reduced and completely eliminated for some pure EVs. The practice can save time and cost as well. Electric vehicles give consumers a new option, while still offering high levels of mobility, vehicle performance, reliability, and safety. [13].

The benefits can be divided in two groups as followed by [13]:

a) POTENTIAL BENEFITS FOR OWNERS

- Lower operating costs
- Lower maintenance costs
- Less susceptibility to volatile fuel prices
- Quiet ride
- Convenience (home charging for all-electric and plug-in hybrid vehicles eliminates/reduces need to fill-up at gas stations)
- Opportunity to make a "green" choice

b) POTENTIAL BENEFITS FOR THE ENVIRONMENT

- Reduced emissions of harmful air pollutants
- Increased energy efficiency
- Reduced oil dependency

- Reduced vehicle noise
- Optimized use of electricity infrastructure
- Reduced emissions of greenhouse gases

The electric vehicles are the environment friendly vehicles. They have the benefits of providing better air quality from the use of very low and zero emission vehicles and reduced on-road vehicle noise.

The concept of time-of-use electricity pricing can provide cheaper electricity during off-peak times such as overnight and weekends. This will inspire consumers to recharge their vehicles when electricity demand is lower at night, helping to optimize use of electricity infrastructure and increase energy efficiency [12], [13].

Another advantage of these vehicles is the recyclable batteries that are installed inside the vehicles. These rechargeable batteries have the rate of almost 100 percent of the recycling ability, and this can keep the environment much cleaner.

There are some disadvantages that can be mentioned. The major one is the longer time for recharging the battery pack. Depending on the type of charger, it may take more than twenty hours to recharge the whole battery pack. One great solution is to install Level 2 or Level 3 charger for faster charging. Though level 2 and level 3 chargers are quite costly at present, but soon the installation cost for these chargers may reduce with the increasing number of sales.

Another disadvantage of electric vehicles is the weight of the battery pack. Because the battery needs to do more operation than conventional car batteries, electric car batteries need to be connected together into arrays to provide additional power. The collections of the batteries are heavy. Some of the car manufacturers have come up with a concept of making the car body light enough to defuse the battery weight of the car [12].

2.6 EXISTING DESIGNS

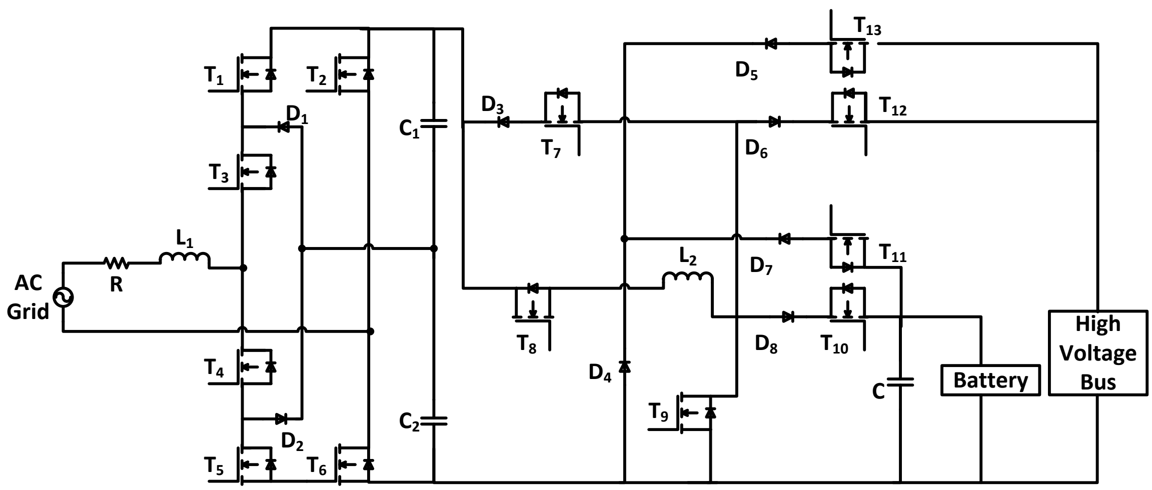

Fig 2.4: Circuit Diagram from Dylan and Khaligh [5]

The converter that is proposed by [5] is a bi-directional multi-level AC-DC/DC-AC converter. This is integrated with a non-inverted buck-boost converter that has an integrated high-voltage bus. The multi-level AC-DC converter is chosen for its ability to supply current to or from the grid with near zero current harmonics and unity power factor. The low device stresses and small filter make it more feasible for this high power application. The non-inverted buck-boost converter with an integrated high-voltage bus is chosen because it only requires one high-current inductor and incorporates the HEV high voltage bus into the design. In combination, these two circuits form a converter that is capable of four different modes of operation, which are plugin charging of the battery, vehicle-to-grid discharge of the battery, high voltage bus charging the battery for regenerative braking, and battery discharge to high voltage bus for supplying power to the HEV. The number of switches is more in the design. As a result the conduction loss can be more in the system [5].

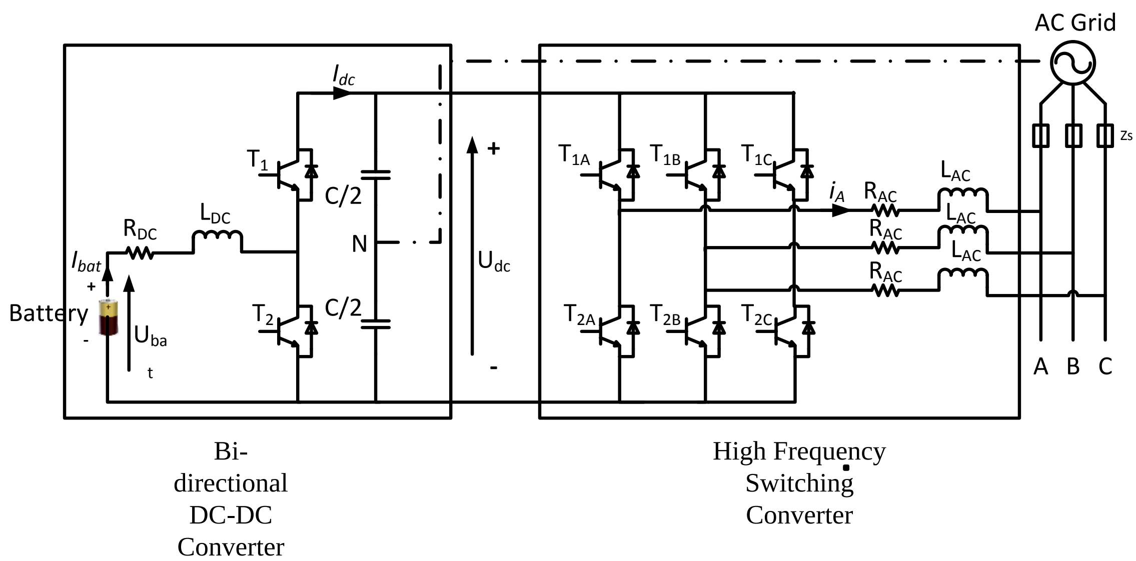

Fig 2.5: Circuit Diagram for Gallardo and Montero [6]

Ref [6] presented a three-phase bidirectional battery charger which is capable of both Grid to Vehicle and Vehicle to Grid operation modes. The system includes one bidirectional DC-DC converter and one bidirectional DC-AC converter. The DC/DC converter is in charge of increasing the battery output voltage to the suitable inverter input voltage. The voltage in the inverter input is fixed to a constant level. The bidirectional inverter performs the function of converting the DC values to the suitable AC values in order to inject sinusoidal currents in phase with the voltage into the grid. A three-phase three-leg topology with mid-point DC bus has been used for the bidirectional inverter. The control strategy that has been proposed for the charger claims to have the capability of few things such as demanding or injecting a sinusoidal and balanced source current with unity displacement power factor. The controller is also capable of improving the power quality. The system is able to reduce the Total Harmonic Distortion (THD) but not less than 8% and it is over the IEEE 519 standard [6].

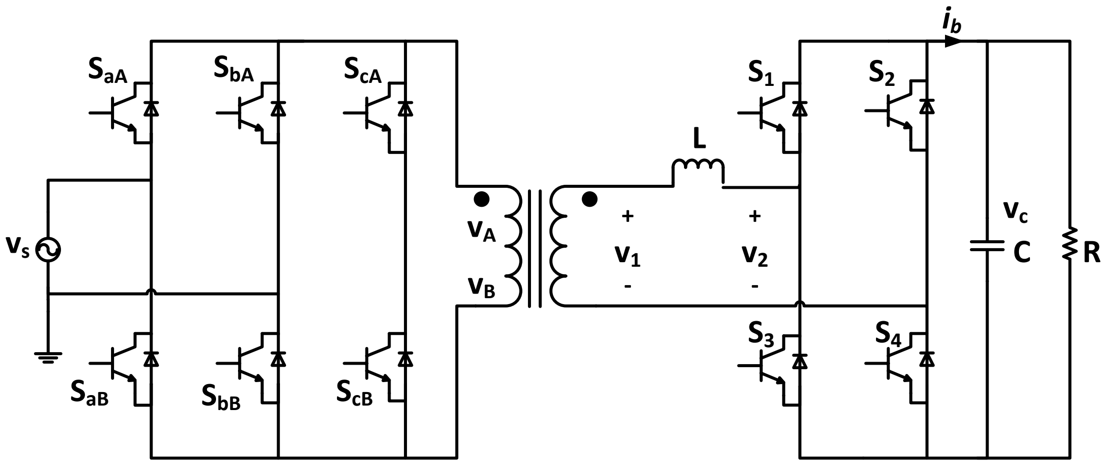

Fig 2.6: Circuit Diagram for Nathan et al [7]

The design that is proposed by [7] has the bidirectional capability with single and three phase input. The system is designed to provide power factor correction for single phase input and can control power factor for three phase input. It is claimed that the system has isolation and voltage matching ability with high frequency transformer that offers low volume, weight and cost and the condition is suitable for V2G operation. The power in the system is being controlled by the duty ratio. Duty ratio has been defined by the phase shifting of one sinusoidal wave and one square wave. A voltage controller has been introduced in the system to make the power factor unity. The system is able to reduce the harmonics but still low order harmonics remains. A total number of ten switches are included in the system. That is why the switching loss is more in the system since it has more number of switches [7].

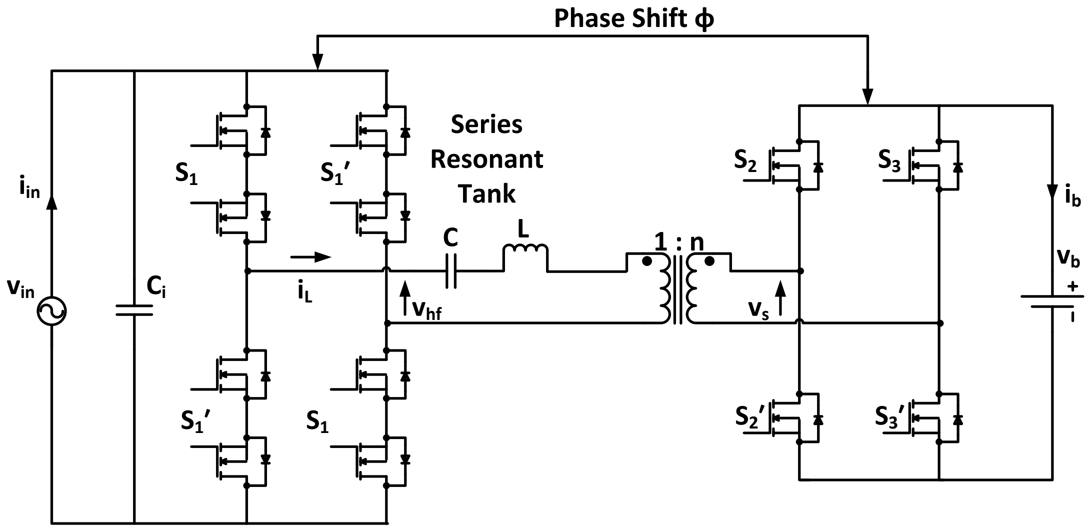

Fig 2.7: Circuit Diagram for Vaishnav and et al [8]

Ref [8] has proposed a single stage bi-directional converter which has two active bridge converters with an intermediate high frequency ac link. High frequency link impedance has been made here by a series resonant tank. For isolation and voltage conversion, a high frequency transformer has been introduced. The phase-shift between the input and output side active bridge converters has been controlled by phase shift modulation technique at a constant switching frequency. This technique allows bi-directional power flow in the system. Due to achieve some advantages such as increased efficiency, soft switching, and component counts etc. a high number of switches have been used in the entire system. And this leads to the fact of high conduction losses [8].

CHAPTER 3

VEHICLE TO GRID TECHNOLOGY

3.1 INTRODUCTION

Vehicle to Grid is a technology where power flows from the vehicle side to the grid side. In order to deliver power from the vehicles, they need to be connected with the grid when they are not in use on the road. The vehicles generate power from its battery which is necessary to run the electric motor inside the car. When the consumer does not need to run the vehicle, or if he has extra charge in the battery pack, he can connect his vehicle to the grid and deliver power from vehicle side to grid side. And when the vehicles need to be charged, the power flow can be reversed. Vehicles can draw necessary power from the grid.

Electric vehicles can be powered with batteries or fuel cells. And hybrid vehicles can be powered with batteries and conventional gasoline. Both of them have the energy source present within themselves. And this energy source can power the homes and offices. These cars have enormous battery pack for giving the power to the vehicle. And this battery pack can deliver the necessary power to the grid if it is connected to the power line. From an experiment, it has been seen that an electric vehicle can deliver up to 10KW power which is the necessary power needed for 10 US houses. The main advantage for vehicle to grid technology originates as soon as the vehicle discharges power to the grid when the power rate is high and demanding [14].

Vehicle to grid technology can be divided into three different versions as follows:

- Fuel cell vehicles: In fuel cell vehicles, they convert the chemical energy from fuel into electricity through chemical reactions with oxygen and another oxidizing agent such as hydrogen [16]. The power is stored in the hydrogen fuel in these vehicles. These vehicles can produce power for a utility at the peak usage times. They can be called as distributed generators for this functionality [15]. Hydrogen is currently the most usable agent using in the car. Honda FCX clarity is a fuel cell type car.

- Electric and Plug in hybrid vehicles: Electric vehicles and plug in hybrid vehicles use their remaining battery power to supply energy to the grid after the usage by the consumer. The best result comes if the consumer can connect the vehicle at the peak load demand time. For efficient charging, the vehicle can be plugged in during off peak hours so that it can get charged at a cheaper rate. So, vehicles will be charging during the night time and it will be discharging during day time. The vehicles will be functioning as distributed generators while discharging. Nissan Leaf, Toyota Prius are the examples of these types of vehicles [15].

- Solar vehicles: Solar vehicles are the vehicles which are powered by the solar energy. Vehicles with solar power usually equipped with photovoltaic cells. These cells generate electric power from solar energy that comes from sunlight. The converted form of energy stored as direct current electricity. This stored energy later on powers all or part of solar vehicle's propulsion [17], [18]. And the excess amount of charge can be delivered to the grid by connecting the vehicle to the grid.

3.2 ADVANTAGES OF V2G

- Electric and Plug-in hybrid vehicles have batteries installed inside the car. This is called onboard battery pack. The electrical energy that is stored inside the battery pack can be used for peak-shaving and power quality applications. Peak-shaving is the concept to shave the demands of the load when it is peak time. With an advanced technology of smart grid, these vehicles can become an important part of the grid by functioning as distributed system, providing storage and giving grid stability by giving the right amount of power with less pollution.

- Authority has given a standard for the EVs and PHEVs to provide an amount of 1MW total power to the grid by connecting them. A single vehicle is capable to provide up to 19KW for home appliances and 16KW for office locations. For that around 200 vehicles is needed and the number of vehicles in the road is increasing day by day. Some of the vehicles may have limitations for providing the amount of power due to their necessity, and for that reason it is very essential to increase the number of the vehicles.

- Grid integrated electric vehicles can be gathered all together for discharging and transferring the power to the grid. The whole troop can be treated as one single electric power source. Based on the distribution capacity of the energy, different energy markets can be chosen by an aggregator to sell the gathered energy. One controller can be designed to control the whole process.

- On average most of the vehicles spend about 90 percent of the whole time sitting idle. This large amount of time can be utilized effectively by selling the excess energy while the demand is very high. It will give the consumer back a good amount of money. And a huge number of cars can make a good impact on grid by selling the surplus energy and the owners can get some cash back which probably they spent for the gasoline. And necessary manufacturing change such as battery architecture, smart meter, user interface etc. can be done to implement the bi-directional power flow [9].

3.2.1 BENEFITS:

- Peak Load Leveling: Vehicle to grid concept helps to provide power to the grid when the demand is high, named as peak shaving, and taking the charge at night when the rate is lower for charging, named as valley filling.

- Financial: Consumer can get the financial benefit from V2G. A simple calculation is shown below:

    - Connected for 12 hours per day (6 pm–6 am) 365 days * 12 hours = 4380 hours/year

    - Average historic price paid for regulation = $35/Mega Watt hour

    - Average Regulation price during valley load periods = $28/Mega Watt hour

- Per Vehicle: 4380 hours * $28 * 0.015 MW = $1800 annually [9]

- Renewable Integration: Electrical and plug-in hybrid vehicles can be a good alternate for wind power in the sector of renewable energy. Vehicles can be integrated with the wind power generation system to store excess energy during windy periods. And later on put it back to the grid when the demand is high. In this way vehicles will be able to stabilize the intermittency of wind power.

- Protection during Power Outage: Vehicle to grid concept can play an important role during power outage. One can plugged his car with backup uninterruptible power supply unit of his house. As one car may produce around three kilowatts of continuous power, the consumer can run most of his electrical appliances with that amount of power to fulfill his needs during power outage.

3.2.2 RISKS:

- Battery Life: Usually the Li-ion batteries that have been used in the electric vehicles have a life of 1000 cycles. The usage of the batteries does not make any changes to the number of cycles. This battery can be used as transportation purpose or can be used as other purpose. So, if the battery has been plugged again and again for the vehicle to grid purpose, it will surely lessen the number of available cycle left in it. A sample calculation has been shown here for the additional cost.

- A pack of Li-ion battery with 35kWh storage capacity costs around $35,000 to manufacture.
- Life span of 1000 cycles equates to a cost per cycle of $35.
- Taking in mind that the charging efficiency can be 92% and the battery is charged from 80% depletion at an overnight tariff of $0.10/kWh, then the cost for a charge is $3.01
- After adding this to the cycle cost, the cost to the owner becomes $38.01.
- Therefore the price that the electricity would need to be bought back from the consumer to break even is $38 / (35 x 80%) = $0.86

The cost is around ten times higher than the cost paid by the consumer previously. The only way to reduce this extra cost is to reduce the cost of the battery. One thing here cannot be forgotten that the vehicle will give the charge back to the grid when the demand is high enough to get the cost back to the consumer. Another important factor is to replace the battery pack after the default battery has been used over and over. The noticeable fact is that, only a deep cycle is going to hurt the life span of the battery pack. A shallow cycle does not give much pressure on the battery [9].

- Equipment Life: The engine and other machines of the vehicle are designed to be at turning on and off condition alternatively. A constant turn on can be harmful for the system.

- Capital Cost: For connecting the vehicles to the grid and give the power back, a bi-directional interface is needed. This can be expensive and may require additional onboard inverter. This is because most of the electric vehicles are designed to take the power from the grid only. Though some companies assured that the current vehicles that are designed with vehicle to grid capability will not require any additional hardware, but they are not in the market yet.

- Battery Exchange: Battery pack in electric vehicles plays a vital role. Exchanging the battery pack in a simple architecture vehicle is not complicated. But if the new design with vehicle to grid integration comes up, exchanging may become costly as well as hard. Researchers are not sure about the cost or solidness of exchanging the battery pack in V2G compact system yet and more studies are going on this field.

- Modeling Complexity: The concept of V2G is still an ongoing research. Information has been collected from individual electric vehicle customers to get idea about the new technology. Most of the designs that is proposed by researches are quite complex to implement. So, more studies are required on reducing the complexity and cost for V2G compatibility on electric and plug-in electric vehicles.

- Fragmented Market: Utility companies will be the prime market to buy power from the consumers. So, it is necessary to make it sure that the utility companies are going to get a certain amount of power after a certain amount of time. In this way the companies will become used to with the new concept of V2G. It is necessary to convince them for buying power from the consumers. One way can be storing amount of energy which is quite stable and good in quality. For a stable amount such as one megawatt of power, couples of hundreds of vehicles are needed. All the power can be aggregate in a central substation before transferring to the utility.

- Power Electronics Cost: Electric vehicles are made usually to take charge from the grid. To install the bi-directional ability in the same car, extra cost will be there. This cost is associated with the power electronics of the car. There is a chance that consumer might end up with an additional cost to make the car bi-directional and this cost might exceed the amount of cash back by selling the energy to the grid [9].

3.3 CHARGING TECHNIQUES

A standard has been introduced to use as charger and that is SAE-J1772. This is the standard for North America. The full title of SAE J1772 is “SAE Surface Vehicle Recommended Practice J1772, SAE Electric Vehicle Conductive Charge Coupler.” The main idea is to use a common coupler for all electric and plug-in hybrid vehicle conductive charging system. This standard has been defined to meet the dimensional requirements for all type of inlet and mating connector [21]. A vehicle charger operational requirement include battery temperature management, cooling, converter control, communication means, diagnostic capabilities, vehicle lifetime durability and a user friendly interface [10].

Several charging techniques are available there to charge the vehicles. Depending on the required time for full charge and the amount of current and voltage passing through during charging, all the chargers are categorized into four different categories. The slowest one is called the Level 1 charging and the fastest one is called the Level 4 charging.

Level 1 charging is the slowest charging for electric and plug-in hybrid vehicles. Usually, it is a one phase supply voltage. The required voltage for charging is 120 Volt. Maximum current of 12 ampere can pass through during charging. This type of charger is able to provide 1.44 KW of power to the vehicle. For a 4.4 KWh lithium-ion battery of a Toyota Prius plug-in hybrid car, level 1 charger takes 2-3 hours of continuous charging. The required time seems okay for plug-in hybrid vehicles. But for a full electric vehicle, the battery usually is more powerful. Full electric vehicle like Nissan leaf has its battery pack of 24 KWh. And to charge this enormous battery pack from zero charge to full charge, it may take 16-18 hours for a level 1 charger.

Level 2 charging is a faster charging than level 1 charging. In level 2 chargers usually split phase or three phase voltage has been used for faster charging. Required voltage ranges from 208 volt to 240 volt. A maximum of 32 ampere current can pass during charging. As a result, the charger can provide an input power of 6.6 KW to the vehicle. In order to charge a Nissan leaf from zero charge to full charge, four to six hours is required for a level 2 charger.

Level 3 chargers are faster than level 2 chargers. Level 3 chargers are able to pass 125 ampere current maximum for charging. The chargers use 208 volt to 240 volt 3 phase voltage. These chargers can provide an output power of 20 KW to 26 KW. Mostly used as business purpose at outside charging stations. For a Nissan leaf with 24 KW battery pack, level 3 charger can make it full charge from zero charge within an hour or so.

Level 4 chargers are the fastest one till date. This type of charging is also called DC charging. The chargers are able to provide 400 V dc voltage with the current rating of 125 ampere. Input power can reach up to 50 KW. To charge a 25 KW battery fully, this charger needs only 30 minutes. These chargers are used at outside on route [20].

A summarized table is given in the following:

Table 3.1: Different Charging Methods [19]

Charging Method	Nominal Supply Voltage	Maximum Current	Branch Circuit Breaker Rating	Continuous Input Power
Level 1	120 V, 1-phase	12A	15A	1.44KW
Level 2	208-240V, Split phase, 3-phase	32A	40A	6.66 to 7.68KW
Level 3	208 to 240V, 3-phase	100-125A	As required	>7.68KW
DC Charging	400V maximum	125A	As required	<240KW

3.4 GRID INTEGRATION

Integrating the vehicle with the grid for sending the power back to the system, a number of issues should have been addressed. The issues that have to be taken care of for grid integration in order to give power back to the grid are the following:

- Total Harmonics Distortion should be less than 5% by the IEEE 519 standard.
- Power factor should be close to unity.
- State of Charge should be until adequate percentage.

The top two factors are directly related to the grid pollution. If the power that is going to be uploaded to the grid contains harmonics more than the standard limit, which is 5% for total harmonics distortion (THD), then this power is going to be harmful for other consumers.

The power factor is another important factor for grid integration. If the power factor is not unity or not even close to unity, then the power can be defined as polluted power. The power factor is the ratio of the active power (P) to the apparent power (S). The value of the power factor ranges from -1 to +1, where +1 is the best side. Because, if the power factor is unity, that means all the supplied power can be consumed by the load.

State of charge is the third factor for grid integration. The vehicle needs to have at least a good amount of charge that is reserved in the vehicle. Otherwise, after even hours of integration, the vehicle will not be able to deliver any power to the grid and that will be a waste of resources.

CHAPTER 4

DESIGN CONCEPT

4.1 BI-DIRECTIONAL CONVERTERS

Bi-directional converters can be divided into two different types: Bi-directional DC-DC converter and bi-directional AC-DC converter.

4.1.1 BI-DIRECTIONAL DC-DC CONVERTER

The bidirectional dc-dc converter is also called a buck- boost converter. This converter has the capability of making the input DC voltage to boost or buck depending on the Pulse Width Modulation and switching. The conversion of the voltage may occur in any direction. Either from buck to boost or from boost to buck, any type of conversion can be done by varying the modulation index. That is why this type of converter is needed in electric vehicles; plug in hybrid vehicles, and fuel cell vehicles. Bi-directional converters may reduce the cost; it may improve efficiency and also improves the performance of the system. In the electric vehicle applications, an auxiliary energy storage battery absorbs the regenerated energy fed back by the electric machine. With the ability to reverse the direction of the current and power flow of the system, the bidirectional dc-dc converters are being used vastly to achieve power transfer between two dc power sources in either direction.

A block diagram of dc-dc converter is given in the following:

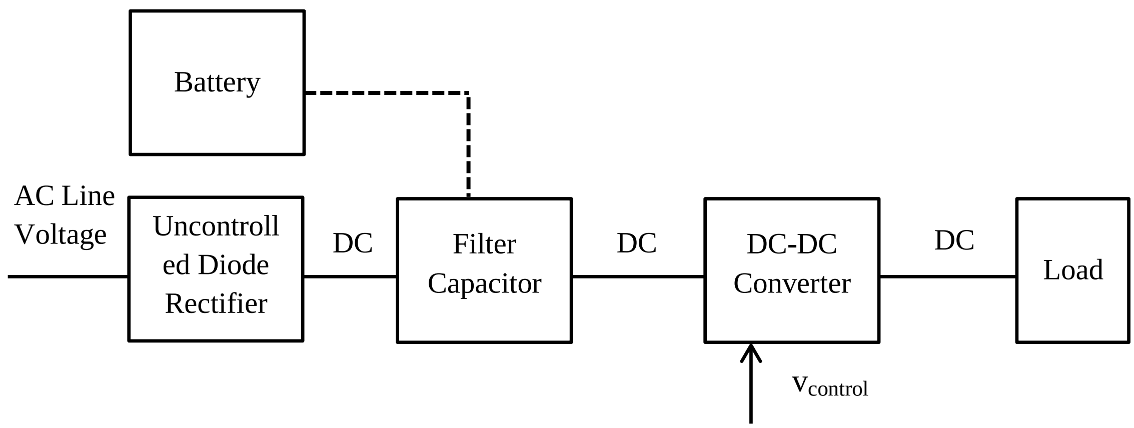

Fig 4.1: DC-DC Converter System [29]

TOPOLOGY

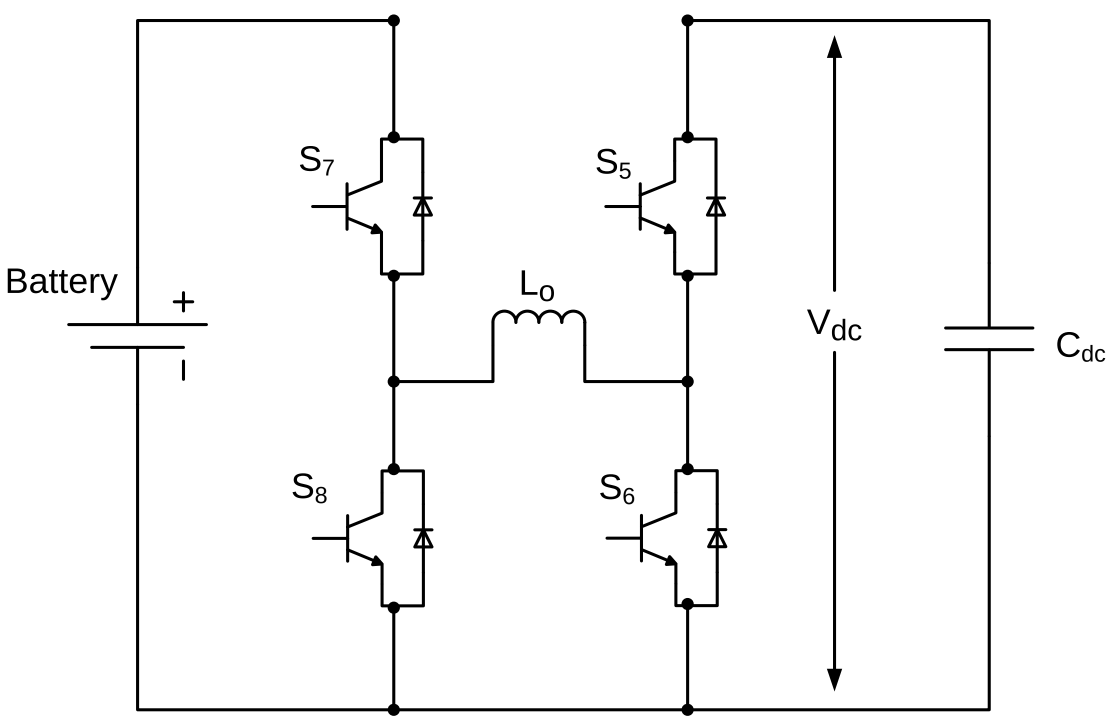

Fig 4.2: Diagram for bidirectional DC-DC converter

WORKING PRINCIPLE

In the topology, the bidirectional function can be divided into two modes. One is charging mode and another one is discharging mode. Two switches named S_5 and S_8 will be turned on during charging mode. And the DC-DC converter will work as a buck converter while charging the battery pack.

During the charging mode switches S_5 and S_8 will be turned on and antiparallel diode S_6 and S_7 will be working as freewheeling diode. In this period of time switch S_5 and S_8 will charge the inductor. In the next cycle switch S_5 and S_8 will be turned off and antiparallel diode S_6 and S_7 will charge the battery.

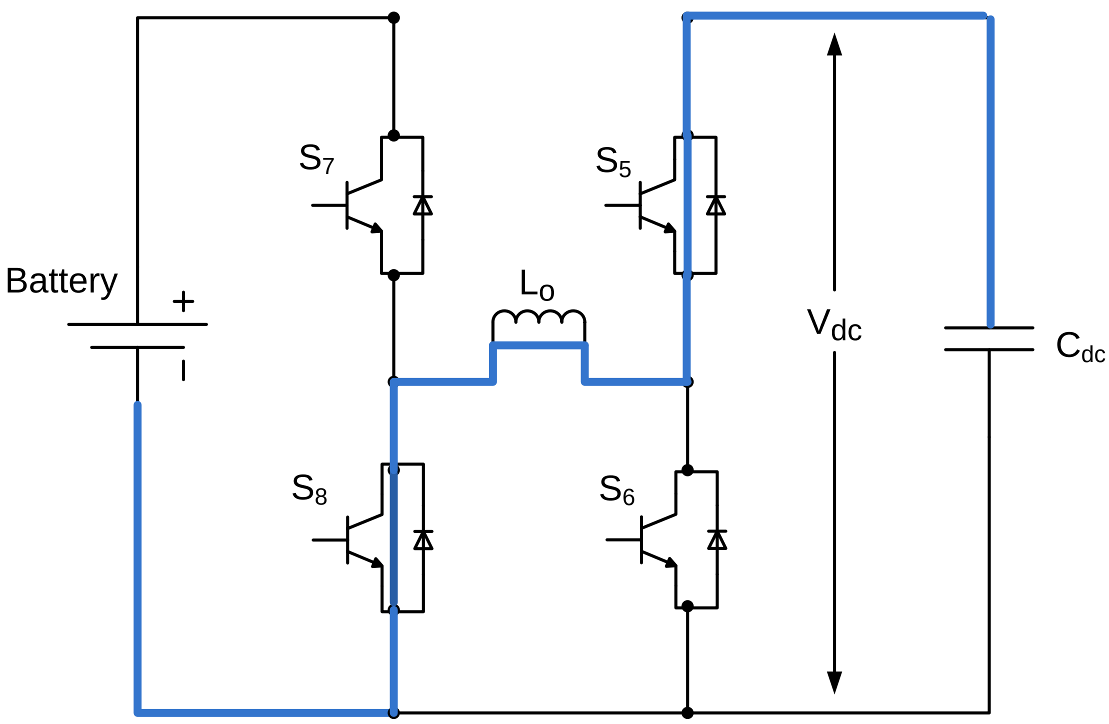

Fig 4.3: Diagram for charging mode

While discharging the dc-dc converter will function as a boost converter. Usually the battery delivers 120V dc to the DC bus. The dc-dc converter will boost up the initial 120V to 380V. During discharging mode switch S_6 and S_7 will be turned on and switch S_5 and S_8 will work as antiparallel diode. While discharging switch S_6 and S_7 will charge the inductor and S_5 and S_8 will deliver the energy to the dc bus when S_6 and S_7 will be turned off in the next cycle [22], [36].

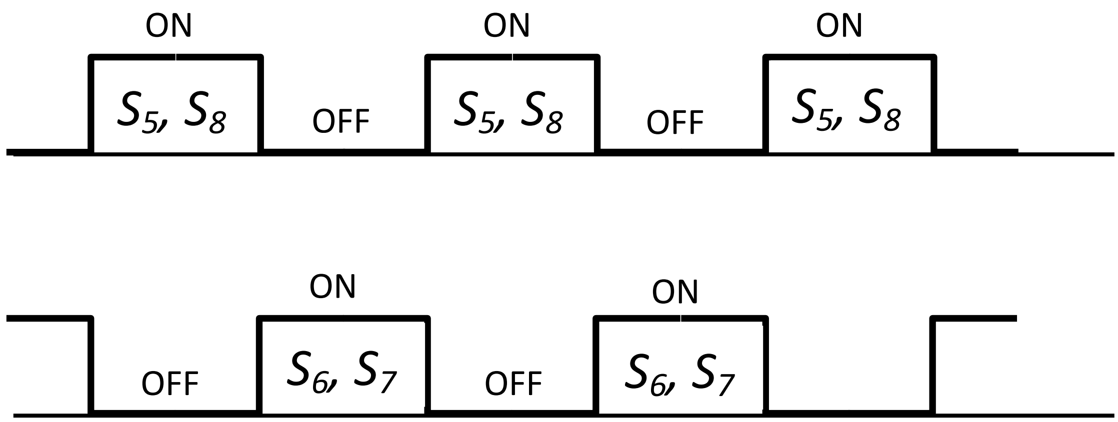

Fig 4.4: Switching combination for DC-DC converter

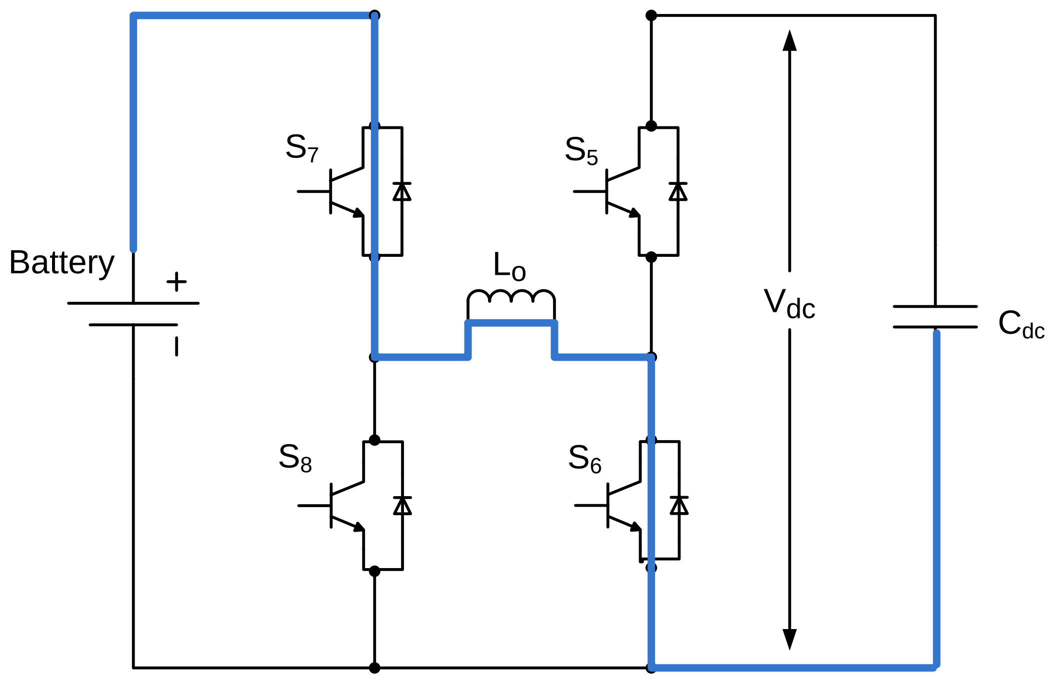

Fig 4.5: Diagram for discharging mode of the DC-DC converter

The DC voltage from the output of the DC-DC converter is 400V. This voltage needs to be converted into 120V.

In order to design the dc-dc converter, at first the coupling inductance should be calculated [25]. To calculate the frequency,

$$f = \frac{1}{2 \times P \times L_O}\left(\frac{1}{\frac{1}{V_{dc}}+\frac{1}{V_b}}\right) \tag{4.1}$$

$$L_O = \frac{1}{2 \times P \times f}\left(\frac{1}{\frac{1}{V_{dc}}+\frac{1}{V_b}}\right) \tag{4.2}$$

Where, f = operating frequency,

P = conversion power,

L_o = inductance

V_{dc} = dc link voltage

V_b = battery voltage

For this topology, some of the parameters are chosen based on literature search [32], [33]. Those parameters and the chosen values are:

P = 3 kW

f = 25 kHz

V_{dc} = 400 V and

Here, V_b = 120 V

With all these values the calculated value of inductance L_o comes as 608 µH.

4.1.2 BI-DIRECTIONAL AC-DC CONVERTER

The bi-directional AC-DC converter have the ability to turn alternating current into direct current during the battery charging mode and convert direct current into alternating current in battery charging mode. So, total function of this bi-directional converter can be divided into two modes: charging mode and discharging mode.

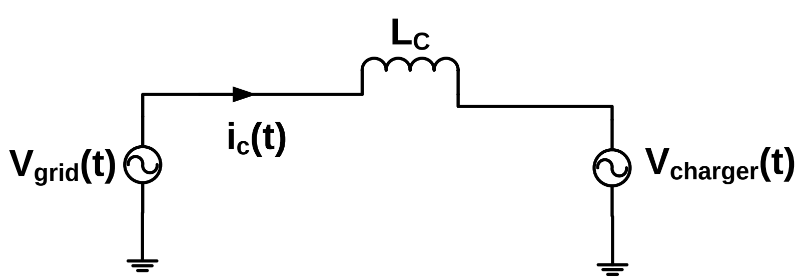

Fig 4.6: Representation of grid and charger [19]

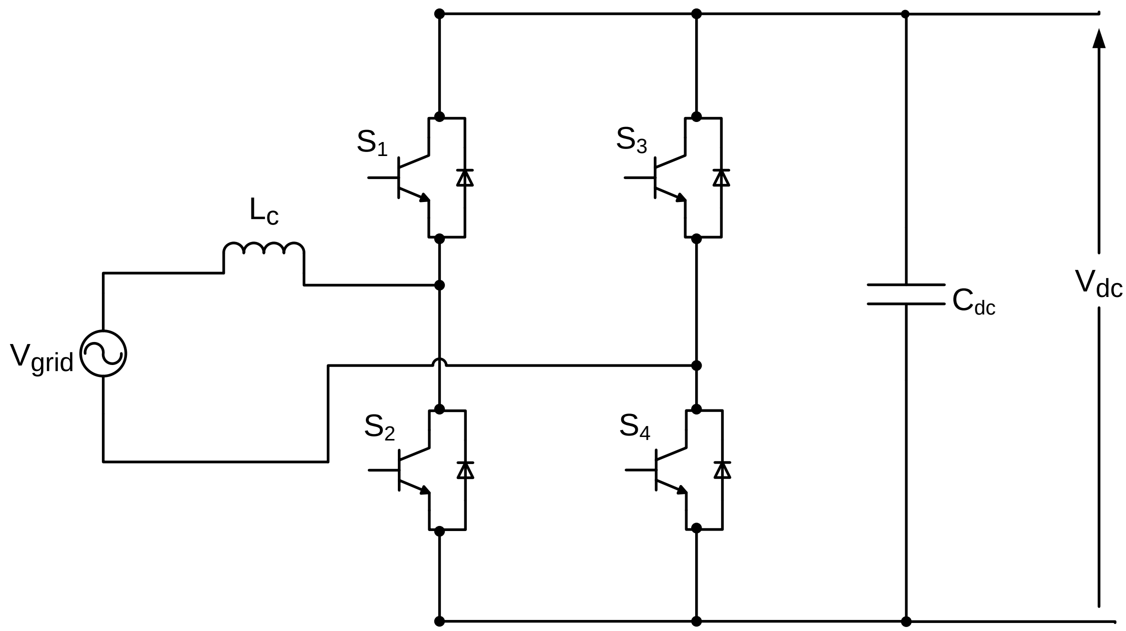

Fig 4.7: Diagram of the AC-DC Converter

WORKING PRINCIPLE

In this topology, the working procedure of the bidirectional converter can be divided into two modes. One is charging mode when the converter functions as AC-DC converter and another one is discharging mode while the converter functions as DC-AC converter [34], [35].

During charging mode, the topology works as a single phase rectifier. It converts the grid current, which is a sinusoidal wave, to the direct current. For the rectifier operation, two switches from two different legs of the circuit turn on depending on the switching signals. Switch S_1 and S_4 gets the signal simultaneously and becomes turned on. These switches turn on when the positive voltage pass through them. During this time switch S_2 and S_3 remains off.

In the next instance when the negative part of the sinusoidal grid voltage pass through the circuit, switch S_2 and S_3 turns on and switch S_1 and S_4 becomes turned off. To ensure the flow from the vehicle side to the grid side, inductor has been used to decouple voltage sources.

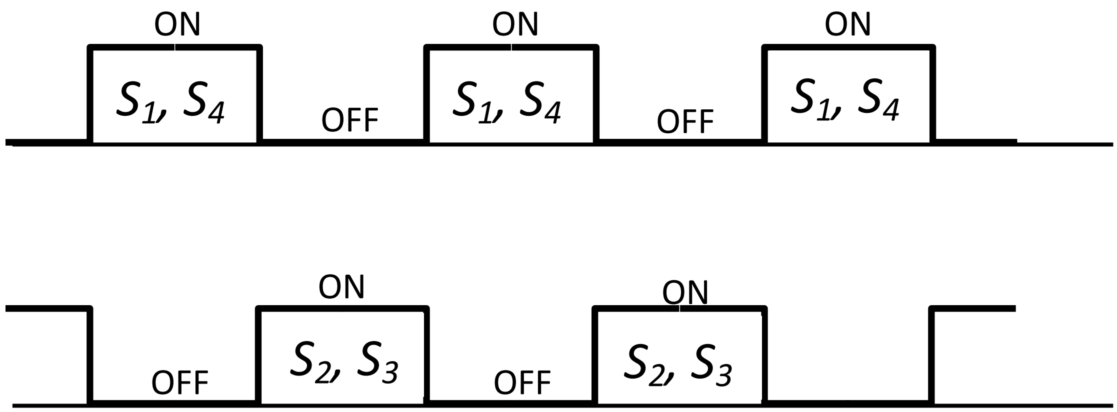

Fig 4.8: Switching combination for AC-DC converter

After converting to dc, this direct current will go to the dc bus. The grid voltage is considered to be a sinusoidal. And the equation for the sinusoidal grid would be:

$$v_{grid}(t) = \sqrt{2}V_{grid}\sin(\omega t) \tag{4.3}$$

Here, v_{grid} is instantaneous voltage and V_{grid} is rms (root mean square) value.

The AC converter voltage can be written as:

$$v_{conv}(t) = \sqrt{2}V_{conv}\sin(\omega t - \delta) \tag{4.4}$$

Where, v_{conv} is the instantaneous voltage of the AC converter and V_{conv} is the rms value of that. δ denotes the angle between the grid voltage v_{grid} and converted voltage v_{conv}.

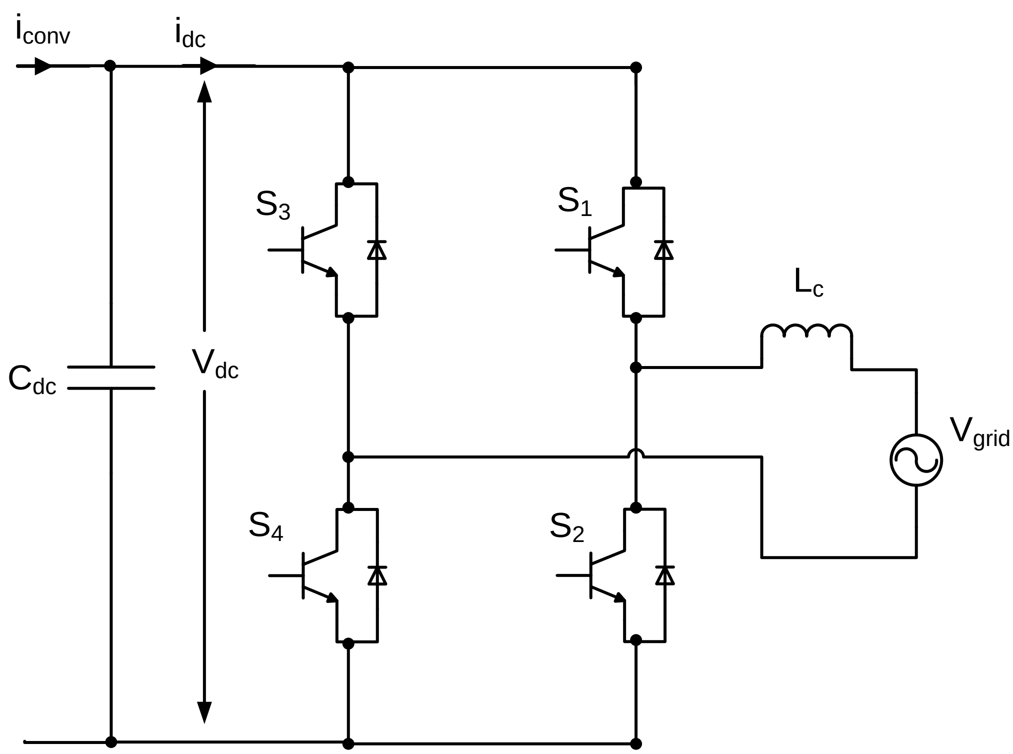

Fig 4.9: Diagram for discharging mode of the DC-AC converter

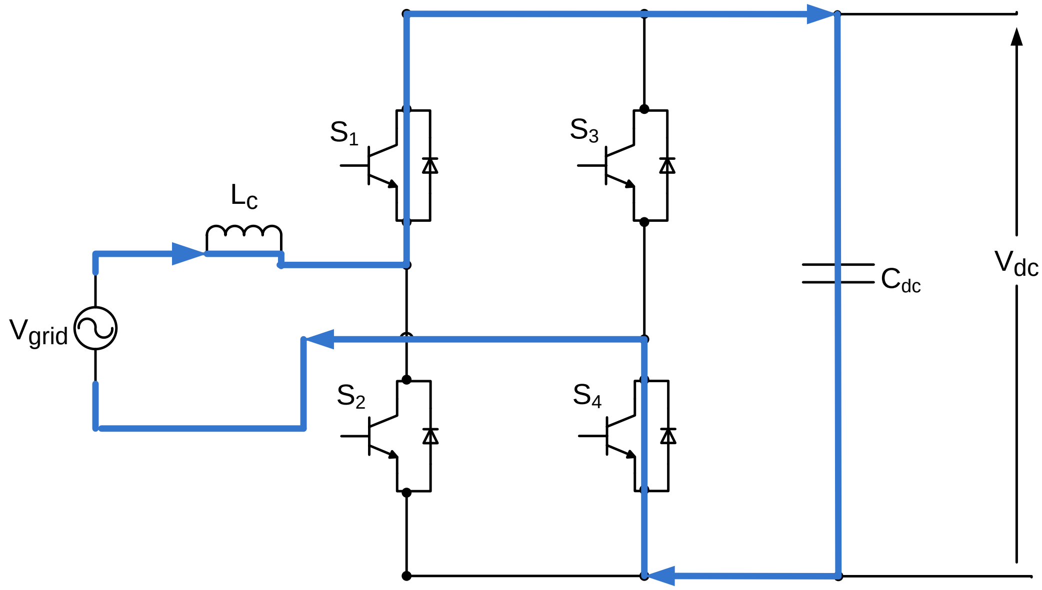

Fig 4.10: Diagram for charging mode of the AC-DC converter positive voltage

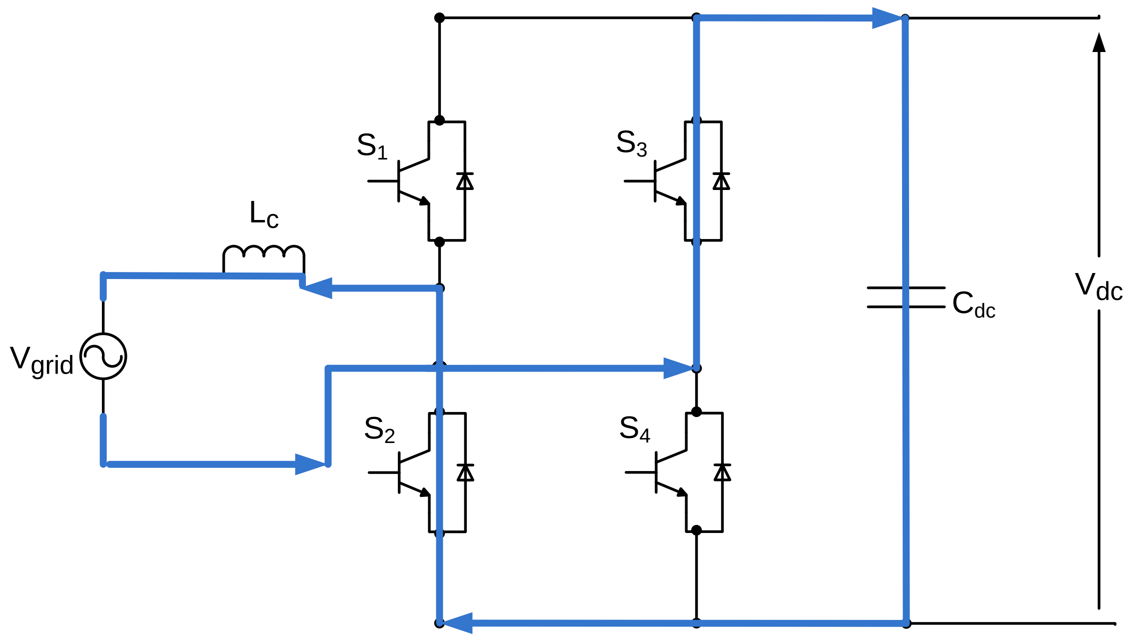

Fig 4.11: Diagram for charging mode of the AC-DC converter negative voltage

The relation between dc link voltage and converter voltage is:

$$V_{conv} = \frac{mV_{dc}}{\sqrt{2}} \tag{4.5}$$

Where, m = modulation index

The grid current can be given as:

$$i_{grid}(t) = \sqrt{2} I_{grid} \sin(\omega t - \theta) \tag{4.6}$$

Where, θ denotes the angle between grid current i_{grid} and converted voltage v_{conv}.

In order to get the switching frequency for the converter,

$$f_{\max} = \frac{V_{dc}}{2 L_C H} \tag{4.7}$$

$$L_C = \frac{V_{dc}}{2 f_{\max} H} \tag{4.8}$$

Where, f_{max} = Maximum switching frequency

L_C = Coupling inductance

H = difference between the upper and lower hysteresis band

From literature study, some values are chosen:

f_{max} = 25 kHz

H = 1 A

And, the calculated value for the coupling inductance is 7.6 mH.

To transfer power from grid to the charger, grid current i_{grid} and converted voltage v_{conv} needs to lag the grid voltage v_{grid}.

The equation for the relation between grid voltage and converter voltage can be written as:

$$V_{conv} = \sqrt{V_{grid}^2 + (I_{grid}^2 \times X_C^2)} \tag{4.9}$$

$$\text{Where, } X_C = 2\pi f L_C \tag{4.10}$$

Instantaneous voltage v_{cap} and current i_{cap} for the dc link capacitor is:

$$v_{cap}(t) = V_{dc} + \sqrt{2}\Delta V_{dc} \sin(2\omega t + \theta) \tag{4.11}$$

$$i_{cap}(t) = 2\sqrt{2} C\omega \Delta V_{dc} \cos(2\omega t + \theta) \tag{4.12}$$

For a lossless system, the dc output (i_{dc}) of the ac-dc converter should be equal to the sum of the current goes to the capacitor (i_{cap}) and the current goes to the dc-dc converter (i_{conv}).

$$i_{dc} = i_{cap} + i_{conv} \tag{4.13}$$

For a lossless system, the power needed for charging the capacitor should be equal in both directions; either from dc side to ac side or from ac side to dc side.

$$\int_{\omega t_{\min}}^{\omega t_{\max}} v_{conv}(t) i_{conv}(t) d\omega t = \int_{\omega t_{\min}}^{\omega t_{\max}} v_{cap}(t) i_{cap}(t) d\omega t \tag{4.14}$$

4.2 CHARGING SCHEMES

Electrical vehicles or Plug-in Hybrid vehicles can be charging in two ways. One of them is on board charging system and another one is off board charging. On board charging system is the system where the charging unit is installed inside the car. Off board charging system is the system where the charging system is installed outside the car.

Off board chargers are the faster charging units. Usually there is no limitation of power rating for this type of charger. Off board chargers are mounted outside the vehicle. So the issue of adding extra weight to the vehicle does not arise or create any problem. Off board chargers can achieve a state of charge (SOC) by 50% or more in about ten minutes for a 240 kW system [27].

For vehicle to grid system on board charging is preferred. On board charging requires an additional charging circuit and it results an increase of total weight of the vehicle. Hence it causes the rise of an extra cost as well. But on board charger has the ability to adopt different charging levels and to match different battery requirements. A vehicle equipped with an on board charger can be charged any place such as at home or parking lots.

4.3 TOPOLOGY FOR THE INTEGRATED SYSTEM

The topology for the integrated charger will be the integration of the DC-DC converter and the DC-AC converter. Both of the converters have the ability of bi-directional power flow and this is the main factor that should have been there in a charger system in order to make it capable of grid integration. In the Figure 4.12 below the integrated charger has been shown:

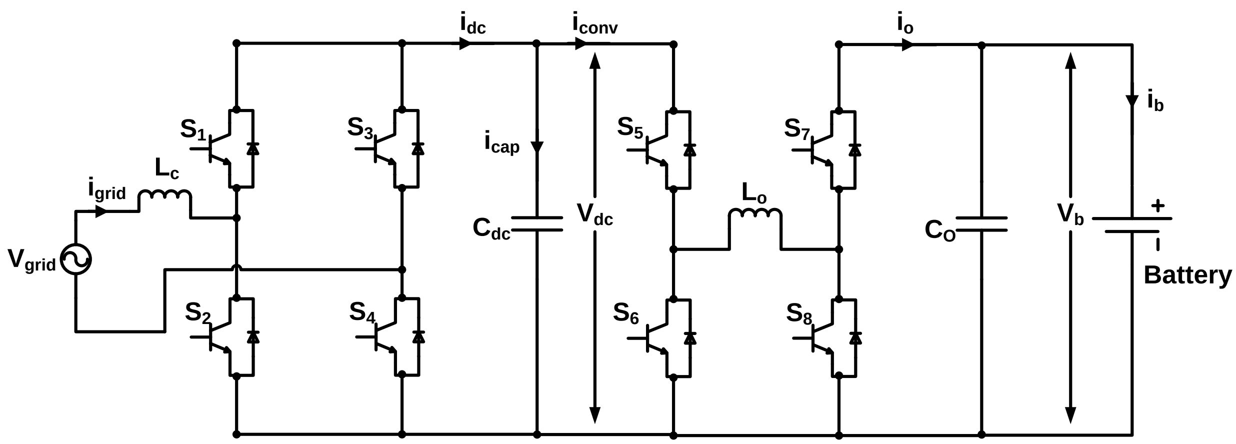

Fig 4.12: Diagram for the Integrated Converter Charger

The topology consists of eight IGBT switches, two inductors and two capacitors.

CHAPTER 5

CONTROLLER DESIGN

5.1 CONTROLLER FOR DC-DC CONVERTER

A controller has been proposed to control the bi-directional buck-boost converter. The controller does the charging and discharging operation for the dc-dc converter. For charging the battery, the controller does the buck operation. And for discharging the battery, the controller does the boost operation. To get the desired operation by the controller, Pulse Width Modulation (PWM) technique has been used.

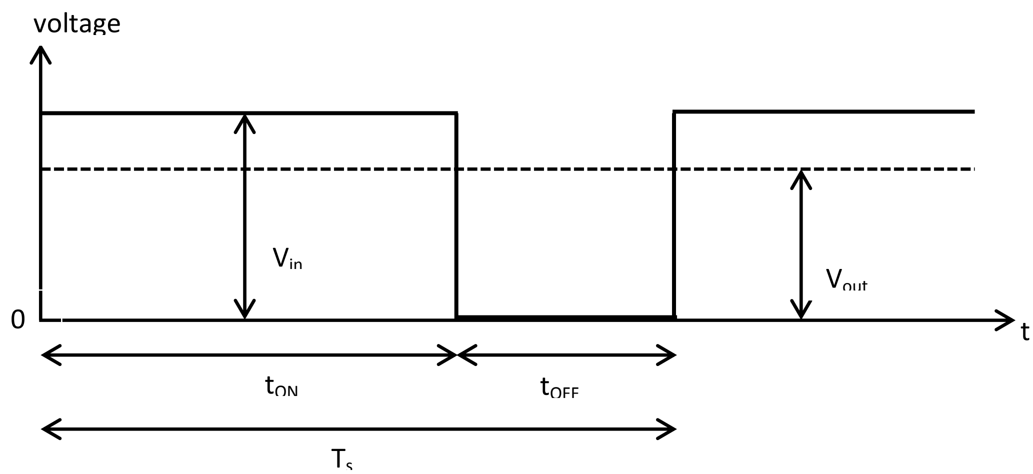

Fig 5.1: Switch mode DC-DC conversion

Here, T_s denotes total switching time period, t_{on} denotes amount of time the switch is on, and t_{off} denotes the amount of time the switch is off. For a complete cycle, the duty ratio is,

$$D = \frac{t_{on}}{T_s} \tag{5.1}$$

Pulse width modulation is a technique that has been used to create a variable analog signal. By applying this technique, switches can be triggered in different times. For buck and boost operation, different switching combinations need to be triggered and for this reason PWM is widely used.

As mentioned before, for buck operation switch S_5 and S_8 needs to be turned on. And for boost operation switch S_6 and S_7 needs to be turned on.

For buck converter, the duty ratio,

$$D = \frac{V_o}{V_i} \tag{5.2}$$

Where, V_o denotes output voltage and V_i denotes input voltage.

For boost converter, the duty ratio,

$$D = 1 - \frac{V_i}{V_o} \tag{5.3}$$

For buck-boost converter, the equation will be:

$$\frac{V_o}{V_i} = D\left(\frac{1}{1-D}\right) \tag{5.4}$$

The output current of the battery is I_b. This current I_b has to be controlled. To control the current I_b, the output current (I_o) of the dc-dc converter should match with the reference current I_{ref}.

For controlling $I_{b,}$ a PI (Proportional Integral) controller has been introduced in the model. PI controller is one type of feedback controller. Feedback controller is a sort of controller which takes the output and feed this into the input again. A PI controller calculates the difference between a measured process variable and a desired output. The controller attempts to minimize the difference known as error by adjusting the process control inputs. And one of the inputs is the output of the system which feeds to the input.

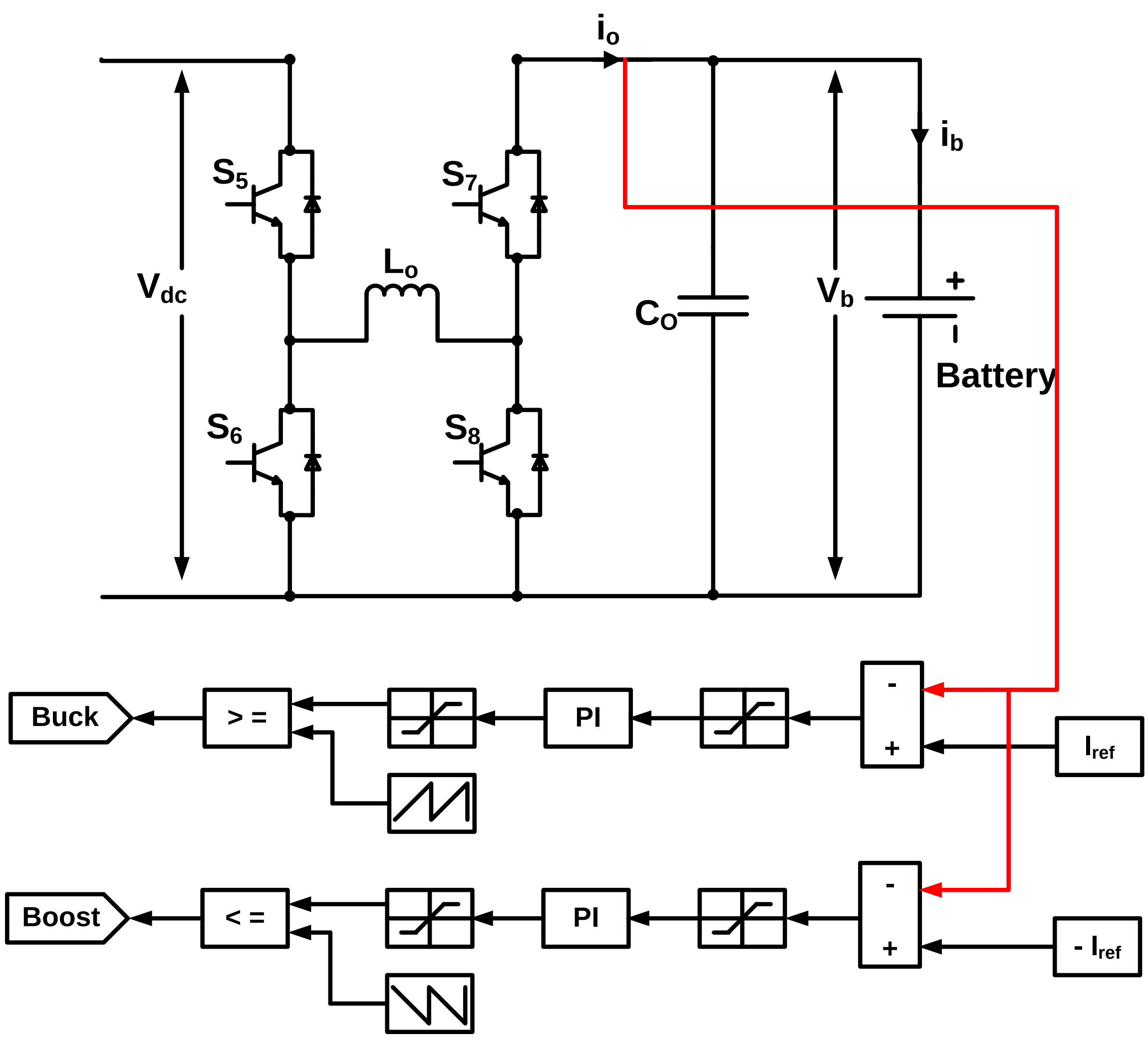

Fig 5.2: Controller of DC-DC Converter

The dc link current has to compare with a reference current. The reference current is I_{ref}. PI controller measures the difference between I_{ref} and the dc link current I_o. The difference of these two signals determined as error. Then the controller generates a control signal to reduce the difference of two signals hence reduce the error. The error can be estimated by sensing the dc link current and the reference current at an instant point.

For a n_{th} instant of time,

$$I_{error}(n) = I_{ref}(n) - I_b(n) \tag{5.5}$$

The output of the PI controller at that n_{th} instant of time is:

$$V_T(n) = V_T(n-1) + K_p\{I_{error}(n) - I_{error}(n-1)\} + K_i I_{error}(n) \tag{5.6}$$

Where, K_p denotes the proportional gain, K_i denotes the integral gain of the voltage controller [28].

The output $V_T(n)$ is then compared with a sawtooth waveform. The sawtooth waveform is necessary to give certain signals to the switches to turn them on in certain times.

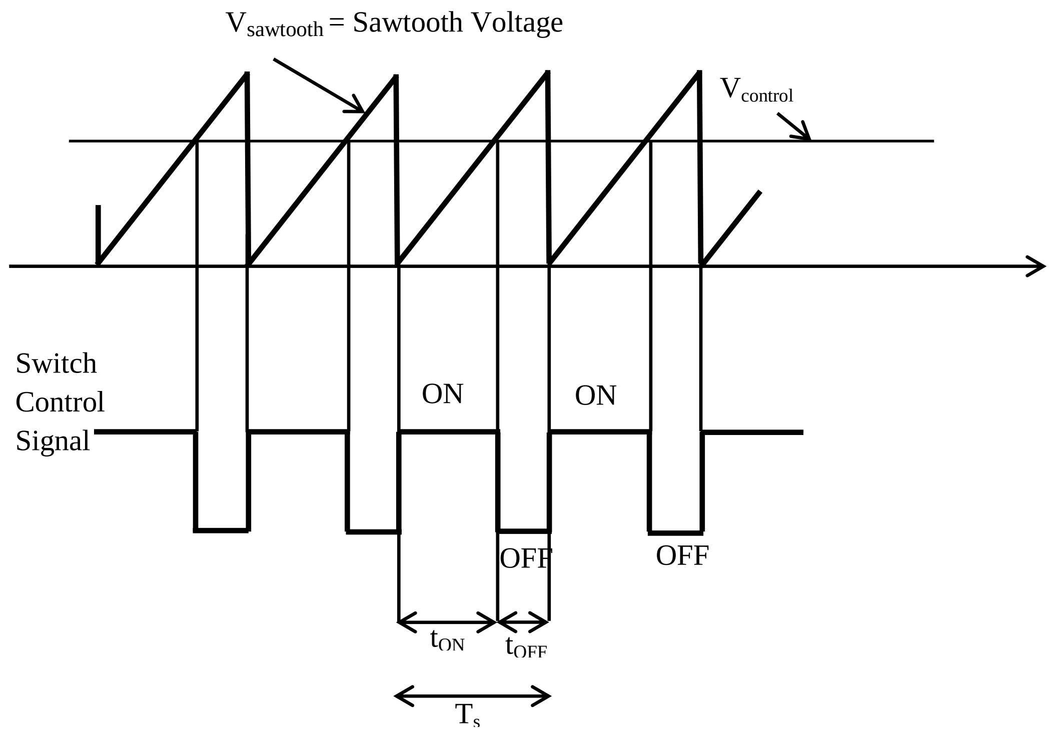

Fig 5.3: Pulse Width Modulator signals [29]

5.2 CONTROLLER FOR AC-DC CONVERTER

The controller has been used to control the bi-directional AC-DC converter. The AC-DC converter is a single phase full bridge converter. The charging current and voltage of this converter has been controlled by the controller. A unipolar switching scheme has been used in the controller.

For a full bridge converter, in unipolar switching scheme the switches S_1, S_4 or S_2, S_3 in the same leg does not work simultaneously. The unipolar switching triggers switch S_1 from one leg and antiparallel diode of switch S_2 from another leg at the same time. And in another instance of time another signal will trigger switch S_3 and the antiparallel diode of switch S_4 at the same time. A triangular waveform is generated and then compared with a control signal. The control signal can have two polarities: positive and negative. Positive and negative signals are the reference signals which are compared with the triangular waveform.

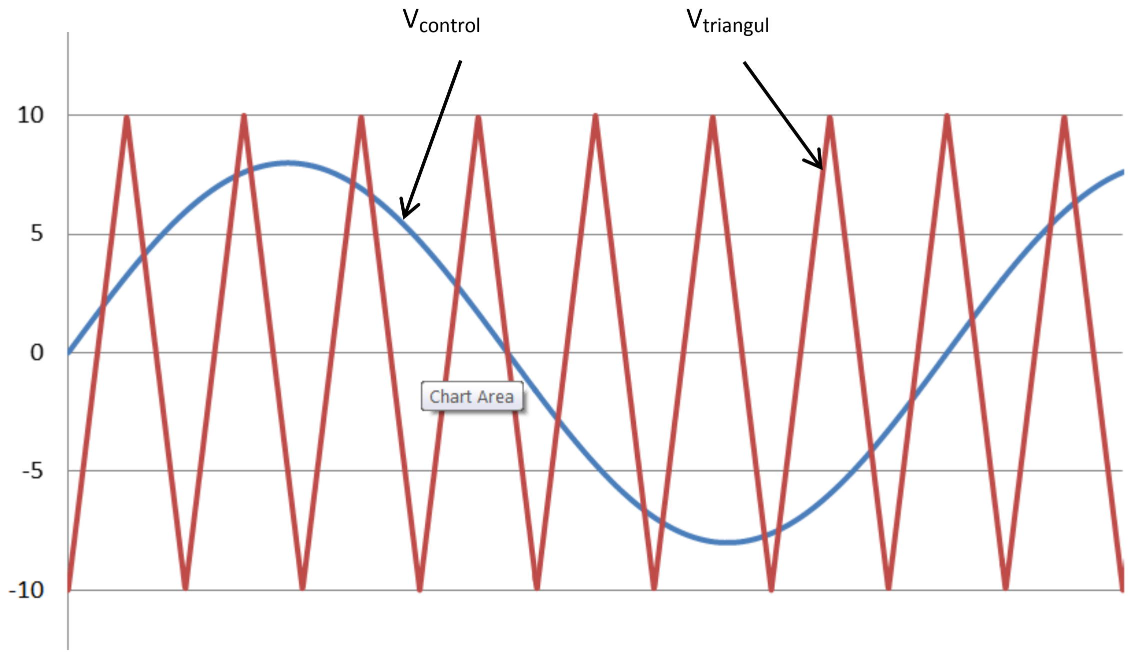

Fig 5.4: PWM with unipolar switching

Here the triangular waveform is $v_{triangular}$ and the control waveform is $v_{control}$.

If the positive control signal is being compared with the triangular signal, two situations can occur.

$$\text{For, } v_{control} > v_{triangular}\text{: } S_1 \Rightarrow \text{ON and } v_{s1} = v_{grid} \tag{5.7}$$

$$\text{And, } v_{control} < v_{triangular}\text{: } S_4 \Rightarrow \text{ON and } v_{s4} = 0 \tag{5.8}$$

If the negative control signal is being compared with the triangular waveform, then two more situations come:

$$\text{For, } -v_{control} > v_{triangular}\text{: } S_3 \Rightarrow \text{ON and } v_{s3} = v_{grid} \tag{5.9}$$

$$\text{And, } -v_{control} < v_{triangular}\text{: } S_2 \Rightarrow \text{ON and } v_{s2} = 0 \tag{5.10}$$

Based on these two equations, four different switching combinations can occur. Those are:

S_1, S_2 ON: $V_{out} = V_{grid}$

S_4, S_3 ON: $V_{out} = -V_{grid}$

S_1, S_3 ON: $V_{out} = 0$

S_4, S_2 ON: $V_{out} = 0$

For unipolar switching the output voltage varies from 0V to $+V_{grid}$, and from 0V to $-V_{grid}$. The output of the AC-DC converter is going to be the input of the DC-DC converter. So, the output of the AC-DC converter needs to be controlled. V_{dc} is the output of the AC-DC converter. This voltage is the dc link voltage between two converters.

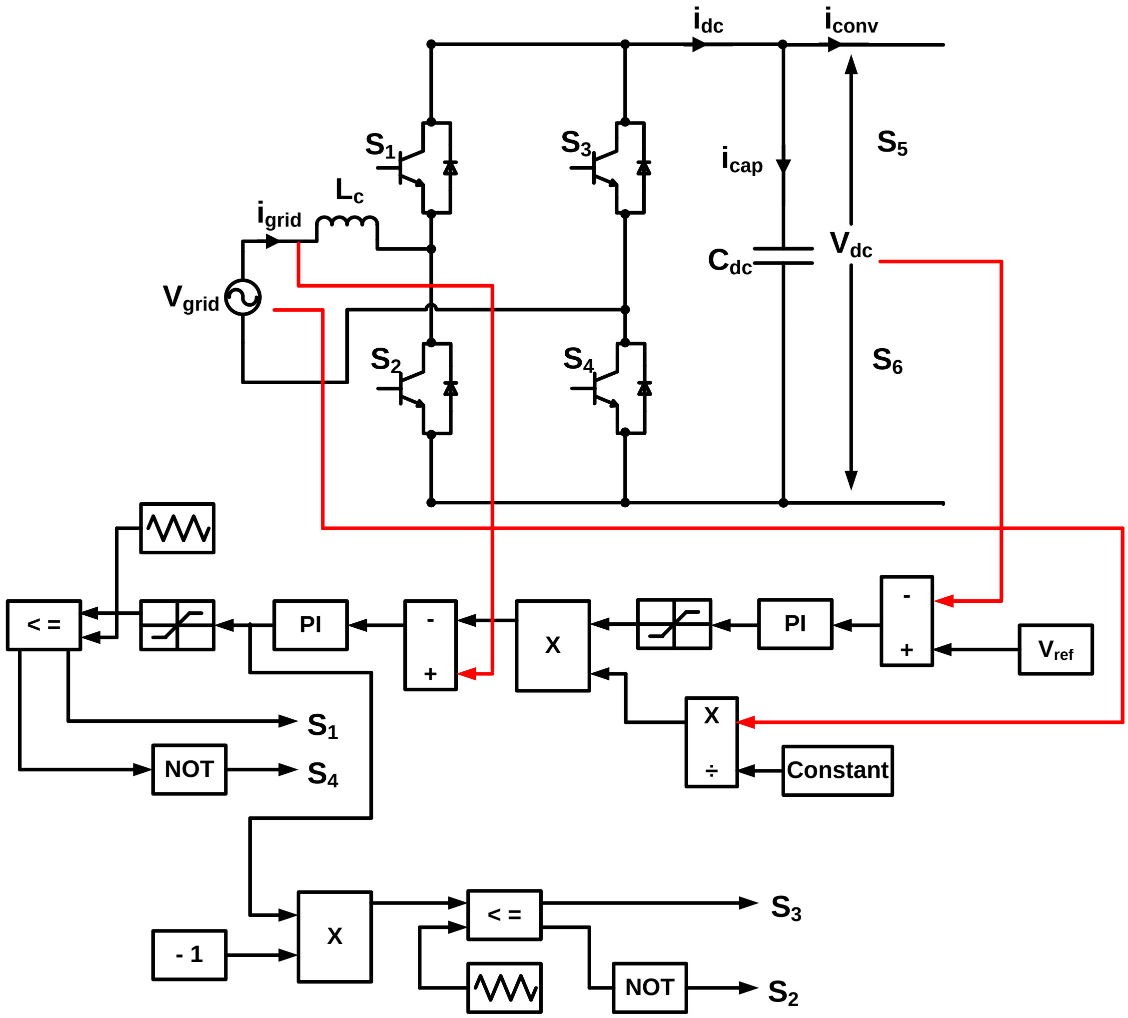

Fig 5.5: Controller of AC-DC Converter

A PI controller has been used in the topology to control V_{dc}. For PI controller to work, a reference voltage is needed. V_{ref} is the reference voltage for the PI controller. The voltage controller tracks the reference voltage and compares it with the dc link voltage V_{dc}. The difference between the reference voltage and the dc link voltage is counted as error. PI controller takes the error as its input and compares it again with the reference voltage. The main motto of the PI controller is to minimize the amount of error so that the dc link voltage can match with the reference voltage. A control signal has been generated by the PI controller to reduce the error.

For an n_{th} instant of time, the equation for the error signal is:

$$V_{error}(n) = V_{ref}(n) - V_{dc}(n) \tag{5.11}$$

The output of the PI controller at the n_{th} instant of time:

$$I_T(n) = I_T(n-1) + K_p\{V_{error}(n) - V_{error}(n-1)\} + K_i V_{error}(n) \tag{5.12}$$

Where, K_p denotes the proportional gain, K_i denotes the integral gain of the voltage controller [31].

Now, the output I_T of the PI controller will work as reference current for the next PI controller. This PI controller will control the current.

Reference current I_T is one of the input of the second PI controller. Another input is the grid current I_{grid}. These two currents are then being compared and the difference of these two currents goes to the PI controller. A control signal is generated by the controller to minimize the error.

If the difference is named as I_K, then any $\mathrm{n_{th}}$ instant of time,

$$I_K(n) = I_{grid}(n) - I_T(n) \tag{5.13}$$

The error signal is then amplified by a gain K. If the control signal generated by the second controller, can be denoted by V_K, then

$$V_K = KI_K(n) \tag{5.14}$$

The amplified signal V_K functions as the carrier wave in the unipolar switching technique. The signal is then compared with a fixed frequency sinusoidal wave and generates switching signals to trigger the switches at different times.

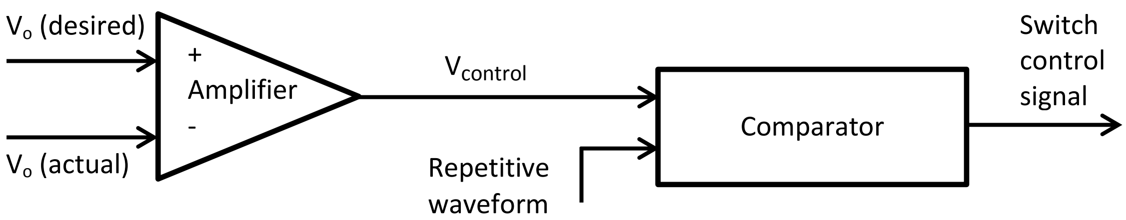

Fig 5.6: Switching signal generation [29]

5.3 Full Design with Controller

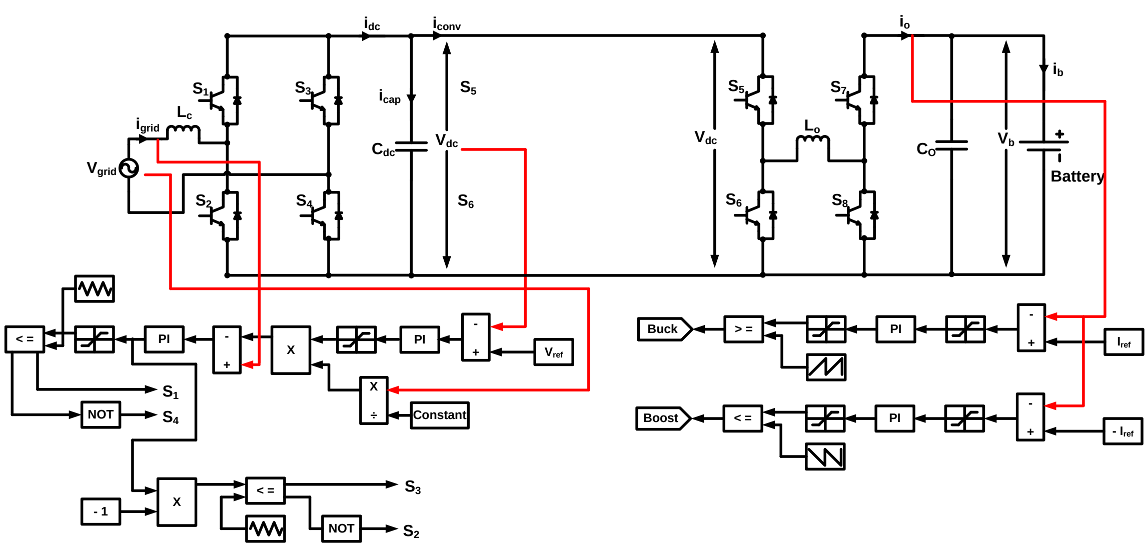

Fig 5.7: Controller of the integrated Converter

CHAPTER 6

SIMULATION AND RESULT

Simulation and analysis has been done in this chapter. The simulations for the converter topologies have been done in MATLAB Simulink ode23tb environment.

Simulations can be divided into two different modes. One is charging mode simulations and another one is discharging mode simulations.

6.1 DISCHARGING MODE

For discharging mode the power will flow from the DC side which is battery side to the AC side which is the grid side.

From the Figure 4.2 the battery has been connected to the bi-directional DC-DC converter. That means the converter can work as both buck converter and boost converter. The converter topology has been shown in Figure 4.2. For the simulation, it has been taken into consideration that the battery has a nominal voltage of 120 V DC. Usually Nickel-metal Hydride (NiMH) batteries deliver 120 V when they are connected with the load. When the vehicle is running then it is considered as a load, but when the vehicle is connected to the grid in an idle situation, it will be considered as a source of renewable energy; because the vehicle will be able to generate power.

Simulation result for the DC-DC bi-directional converter while discharging has been shown in Figure 6.1 which consists of a graph where the voltage has been displayed with respect to time. In the X axis, time has been shown and in the Y axis the respective DC voltage has been shown.

The converter will function as a boost converter while discharging. Two situations can happen in the case of discharging. Either the vehicle can be in idle position and connected to the grid, or the vehicle can be running on road. For this research the first situation has been taken into consideration.

The working principle for the boost operation has been mentioned in the Figure 4.5. Boost converters have been used to increase the input voltage. Here the DC-DC converter converts the voltage to 400 V dc. For getting the input voltage as 120 V and give the output of 400 V is the boost operation. The converter needs 0.9 seconds to stabilize the voltage to 400 V.

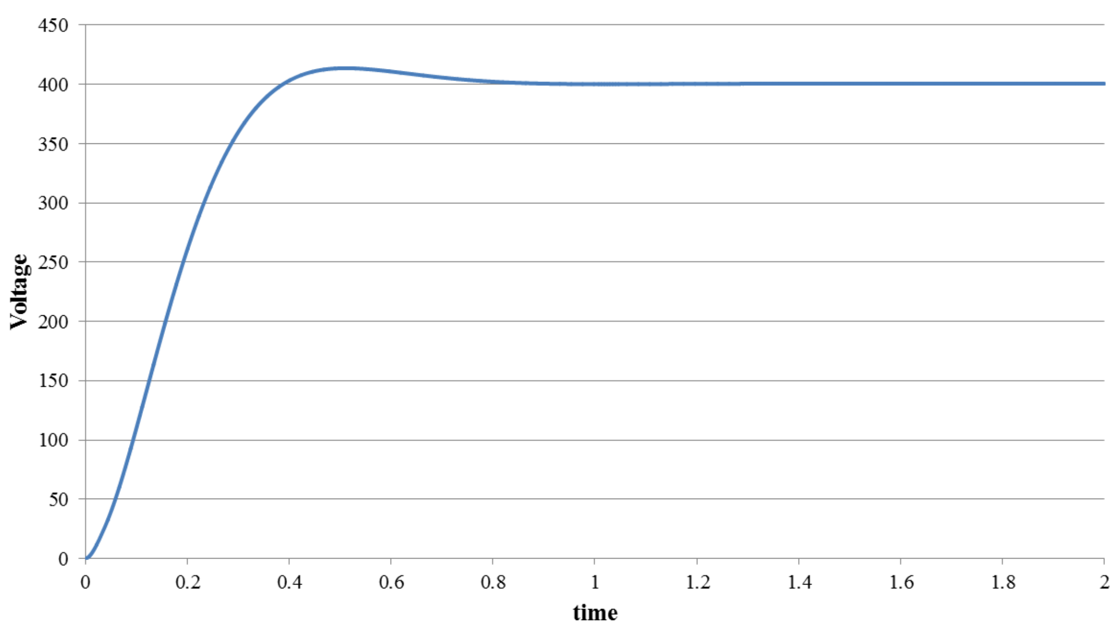

Fig 6.1: Output of DC-DC converter while discharging

The converter boosts up the voltage in order to match the peak to peak voltage of the grid side. The grid side voltage is the regular voltage which can be found in the house hold outlets. This voltage is 120 V rms. 120 V AC rms voltage is equivalent to 170 V AC peak to peak. To match with the voltage of 170 V peak to peak the input of the converter should be 380 V DC voltage.

The output of the DC-DC converter is 400 V and the required voltage is 380 V DC. The input has been taken as 120 V but it may vary from 110 V – 120 V. Besides that the dc link capacitor can store more power to deliver to the grid side. For these cases, a controller has been used to regulate the DC link voltage. The topology for the controller has been given in the Figure 5.2. The primary objective of the controller is to regulate the DC link voltage to 380 V.

In Figure 6.2 the graph has been shown with the controlled voltage of 380 V. The graph is the simulated result of the DC-DC controller. X axis has been taken as the time, and the respective voltage has been plotted in the Y axis. From the graph it is shown that the controller starts controlling the DC voltage from the start of 0.5 sec. From the previous graph, Figure 6.1 it is shown that the voltage reaches to 400 V at time 0.4 sec. As soon as the voltage reaches the peak point that is 380 V, the controller starts working. The reference voltage for the controller has taken as 380 V. The output voltage of the DC-DC converter has to follow this reference voltage. That is why, in the Figure 6.2, graph has shown that the increased voltage has been regulated by the controller since 0.5 seconds and it continues.

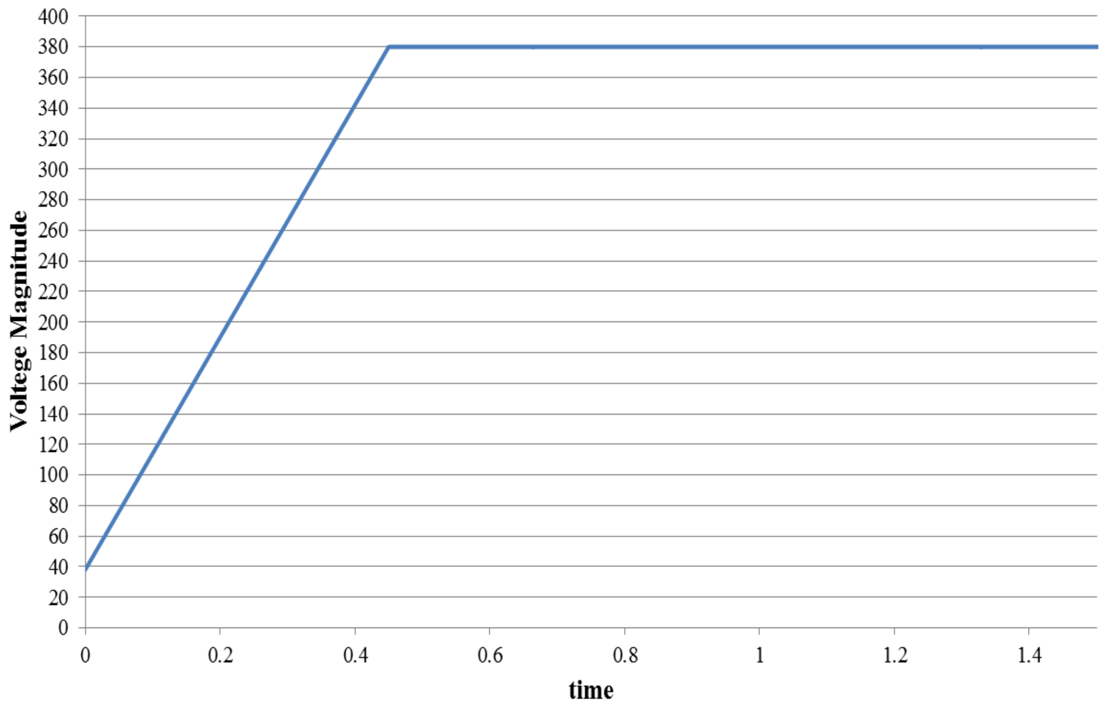

Fig 6.2: Output of DC-DC controller while discharging

After the conversion from the DC-DC converter, the power flows to the grid side. As the grid side is the AC side, so the DC voltage needs to be converted to AC voltage. The DC-AC converter which has been mentioned in the Figure 4.9 is been used for this conversion. Actually, this is also a bi-directional converter which can be work both as DC-AC converter and AC-DC converter. During the discharging mode, this converter functions as DC-AC converter.

For this converter the input voltage is 380 V DC. The desired output is 170 V peak to peak in order to match with the voltage of the grid. In order to inject the power back to the grid two things needs to be taken care of. The first one is the peak to peak voltage and second one is the current. The graph which is displayed in Figure 6.3 is showing the output voltage of the DC-AC converter. The output voltage has transients and oscillation until 1 second, but after 1 second, it becomes stable and starts giving a stable output of 170 V AC peak to peak. In this graph, the X axis represents time and Y axis represents the respective voltage output for that particular time.

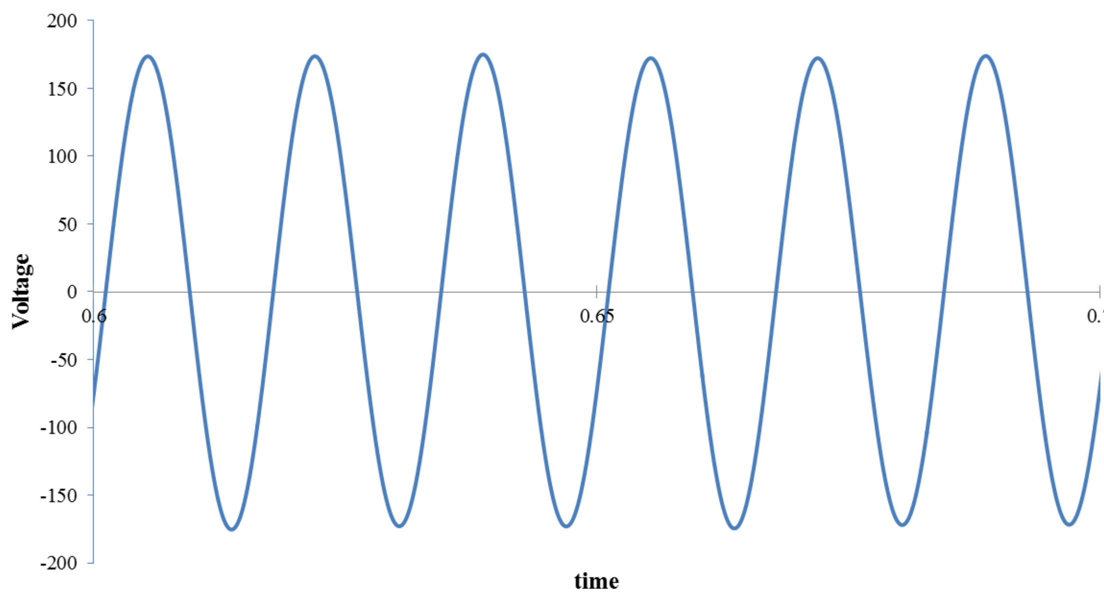

Fig 6.3: Output of DC-AC converter while discharging

The controller which is mentioned in the Figure 5.5 works to control the current and voltage of the DC-AC converter. The controller creates the necessary switching combinations for the converter so that the converter can function as a DC-AC converter to get the desired voltage level and current output.

The output current of the DC-AC converter is shown in the Figure 6.4. 65 A peak to peak AC current can be got from the simulated result. The current needs to be injected to the grid. From research papers, an idea about the injected current can be established. Research papers has shown the magnitude of the current can be range from 10 A to 50 A. The simulated output is 60 A which is pretty close to the output from other research papers. Though the magnitude of the current has exceeded the limit, but it can be said that the current which is shown in the Figure 6.4 has got from the simulation considering that the switches are ideal and the transmission path is lossless. Moreover the fact of power factor has not taken into account. The power factor should be close to unity in order to inject good amount of power to the grid.

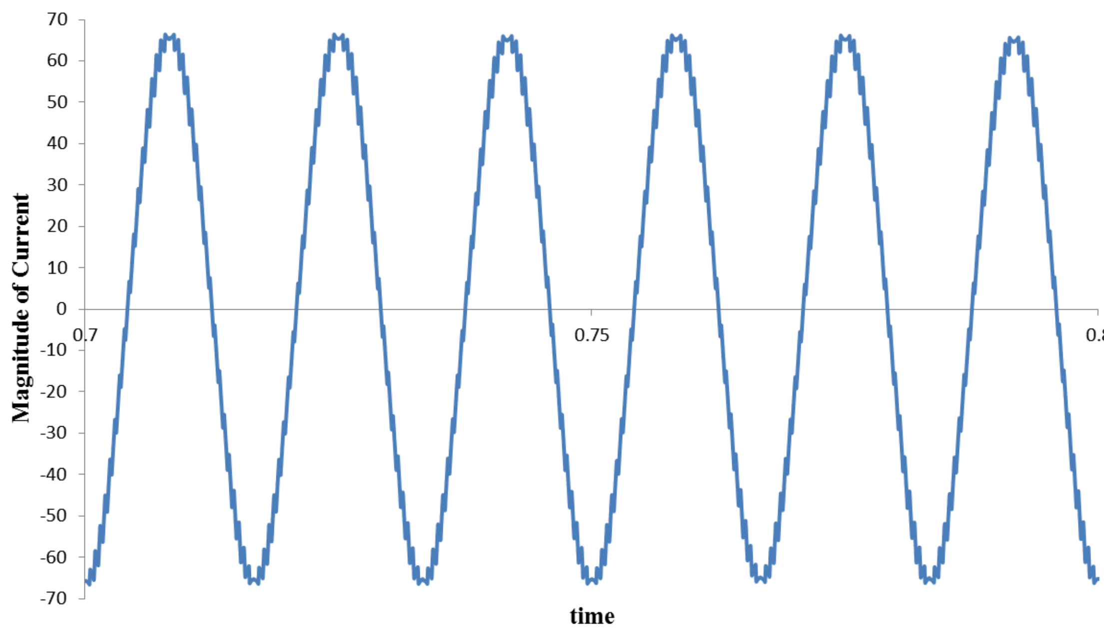

Fig 6.4: Output of DC-AC converter for current while discharging

Another essential factor for injecting power from the consumer side to the grid is harmonics. The converted current may contains harmonics distortion. If the amount of harmonics exceeds the maximum limit of acceptable harmonics to be entered to the grid, then the current can pollute the grid power. The maximum amount of total harmonic distortion is 5% or less as per IEEE 519-1992 and IEEE 1547 recommended practice.

IEEE 519-1992 is the regulation standard for the harmonics limits. And IEE 1547 is the standard for interconnection. So, in order to connect something to the grid that is in order to give the power back to the grid these two standards must be followed by the consumer.

A graph is shown in the Figure 6.5 getting the data from of the current output. The magnitudes of the current in respect to the time have been transformed to the frequency domain. The technique that has been used here is the Fast Fourier Transform (FFT) technique. By using the FFT, in the frequency domain harmonics can be calculated with the magnitude. In the graph 6.5, the X axis of the graph signifies the harmonic order and the Y axis denotes magnitude of the harmonics for the respective order. The fundamental harmonics is the 1st order harmonics which is the magnitude of the peak to peak AC current that is 65.27 A. The fundamental frequency is 60 Hz as per North American standard. The total harmonics distortion (THD) is shown 3.81% which is in the limit of acceptable harmonics distortion.

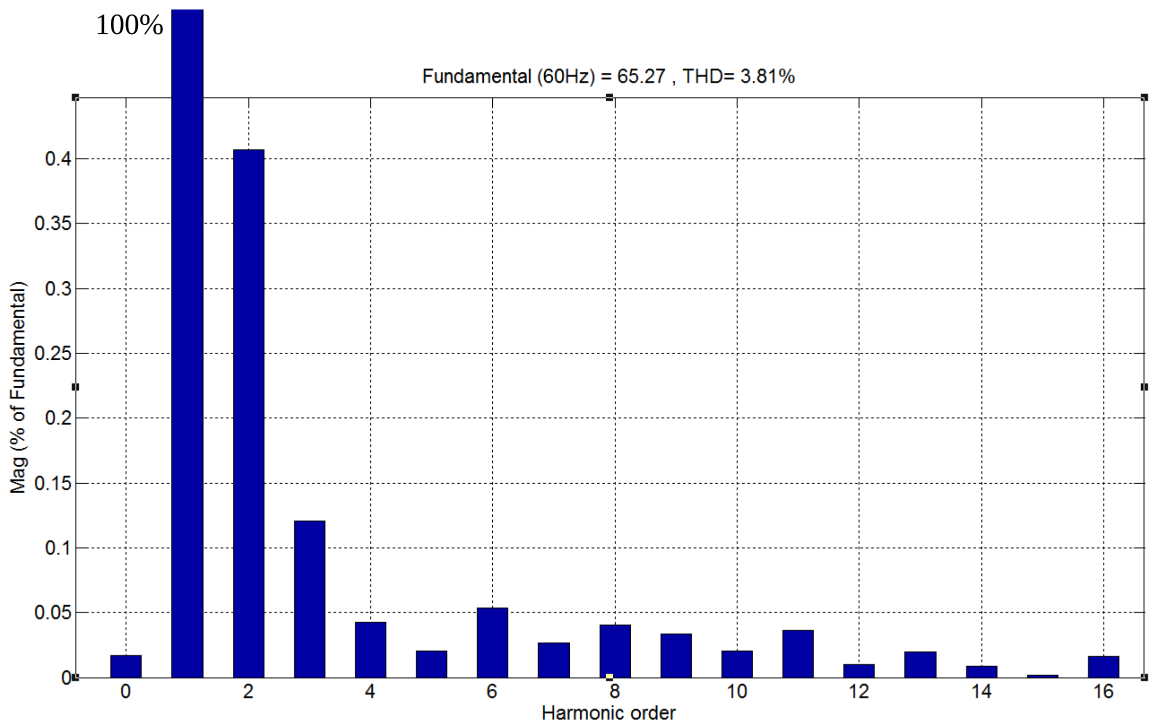

Fig 6.5: Harmonics of DC-AC converter while discharging

From the data of the graph a table can be formed with the values of the harmonics. Table 6.1 shows the details:

Table 6.1: Harmonics with the Magnitude for the incoming Grid Current

Frequency (Hz)	**Harmonic Order (h)**	**Percentage of Distortion**
0	Direct Current	0.02%
60	Fundamental 1st order	100%
120	h2	0.41%
180	h3	0.12%
240	h4	0.04%
300	h5	0.02%
360	h6	0.05%
420	h7	0.03%
480	h8	0.04%
540	h9	0.03%
600	h10	0.02%
660	h11	0.04%
720	h12	0.01%
780	h13	0.02%
840	h14	0.01%
900	h15	0.00%
960	h16	0.02%

From the above data while taking the 1st order harmonics as 100%, a graphical representation can be drawn in Figure 6.6 to give an idea of the other orders of harmonics.

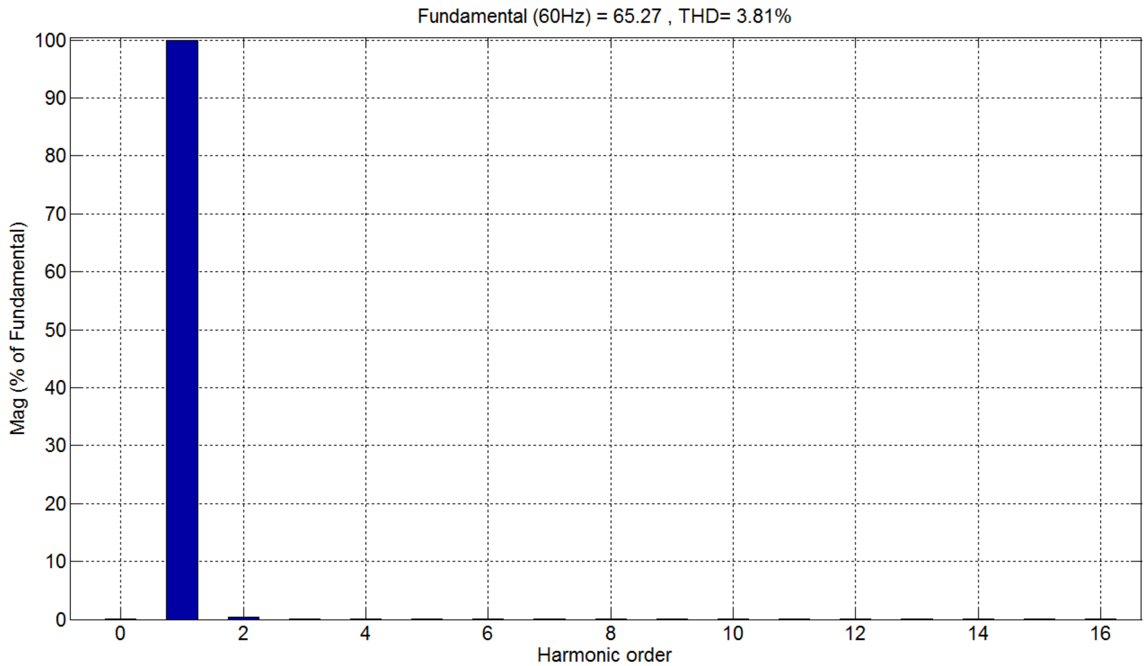

Fig 6.6: Harmonics of DC-AC converter while discharging (Full view)

6.2 CHARGING MODE

The second mode for the simulation is charging mode. In this mode the power flows from the grid side to the battery side in order to charge the battery.

The grid delivers 120 V rms sinusoidal AC voltage which is 170 V peak to peak AC voltage. The voltage needs to be a DC voltage in order to charge the battery. So an AC-DC converter is required to do this conversion. The topology has been given in the Figure 4.10 and 4.11.

The controller controls the charging current and the voltage of the AC-DC converter. In Figure 5.5 a control topology has been mentioned for AC-DC converter controller. The controller changes the switching combinations of those four switches to make the converter function as AC-DC converter. The output voltage of the AC-DC converter is 140 V DC. According to the Figure 6.8 the voltage reaches at 140 V DC at 1.8 second. This voltage needs to be chopped through the DC-DC converter in order to match to the voltage of the battery.

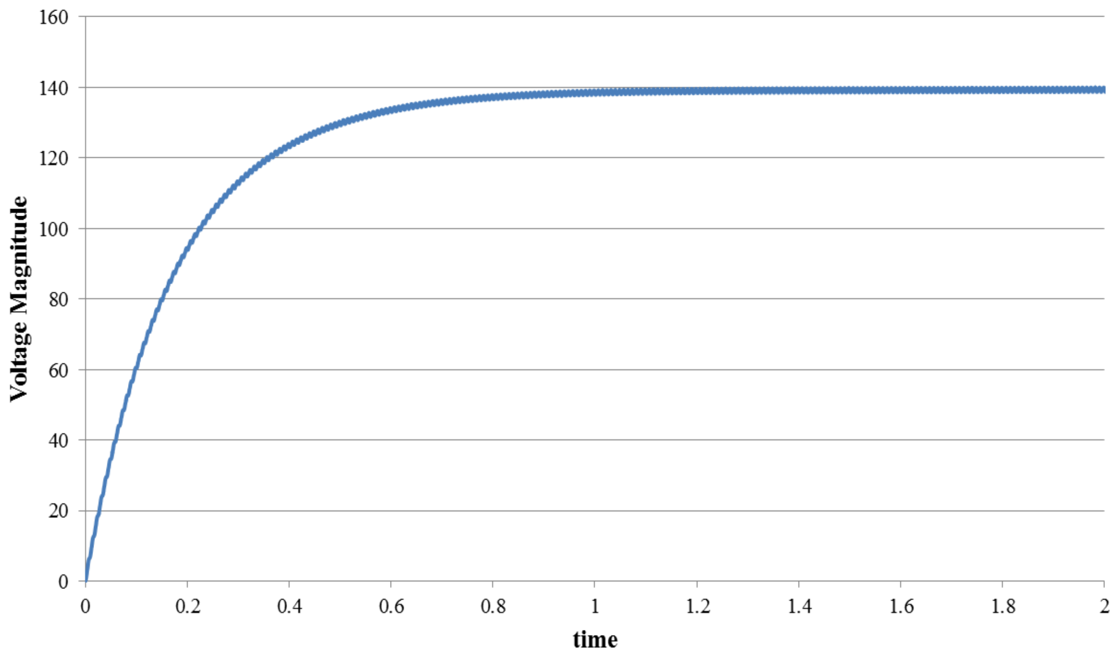

Fig 6.7: Output of AC-DC converter while charging

The current that goes to the dc link is shown in the Figure 6.8. The magnitude of the current is 278 V peak to peak.

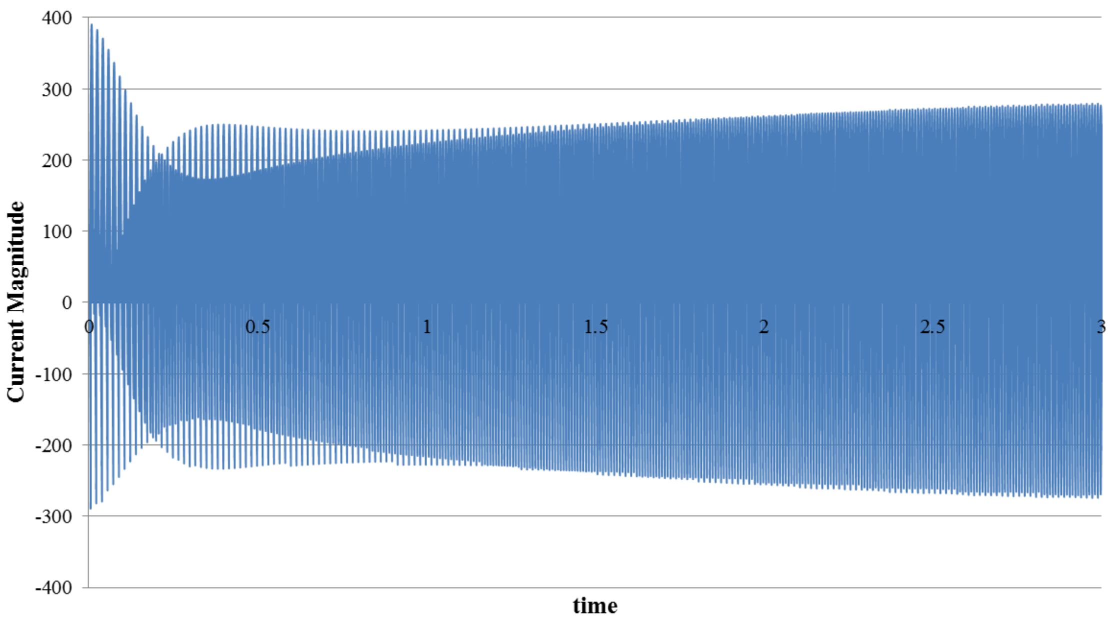

Fig 6.8: Output of AC-DC controller while charging

The harmonics of this current should be in the acceptable range. After the conversion of the AC-DC, FFT technique has been applied to get the magnitude of the harmonics with their respective order. In the Figure 6.9, a graphical representation has been given where X axis denotes the harmonic order and Y axis denotes the magnitude of the harmonics.

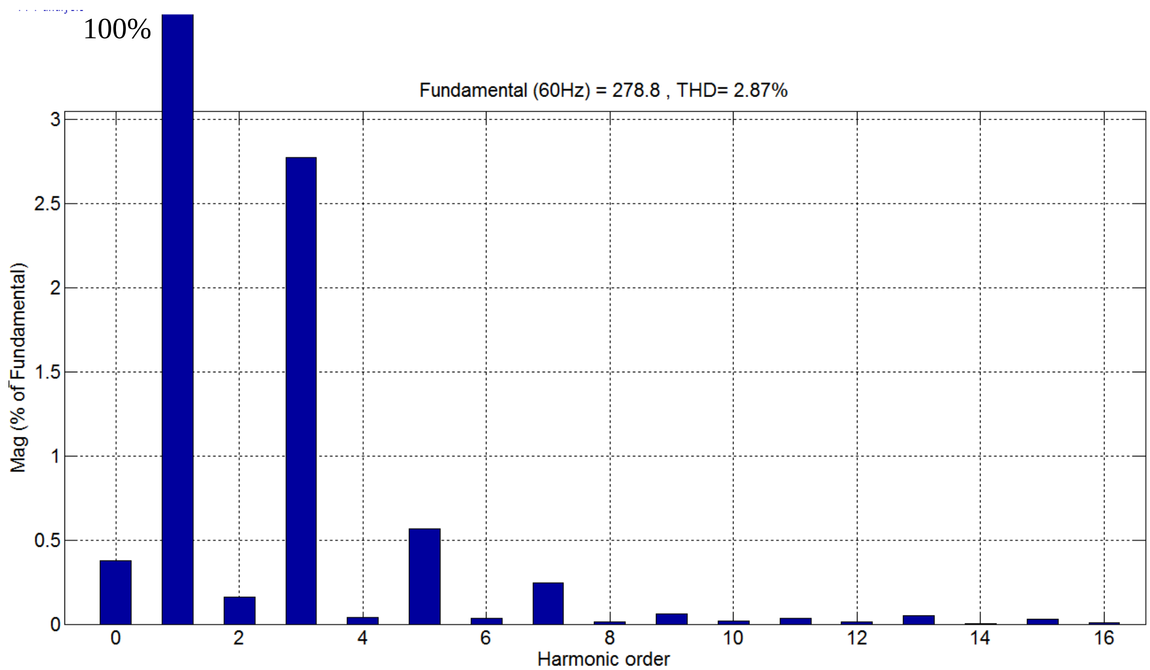

Fig 6.9: Harmonics of AC-DC converter while charging

The fundamental frequency is 60 Hz and for that frequency the magnitude is 278 V AC peak to peak. Table 6.2 shows the respective harmonic distortion for all the harmonic order until 16th harmonics.

Table 6.2: Harmonics with the Magnitude for the outgoing Grid Current

Frequency (Hz)	Harmonic Order (h)	Percentage of Distortion
0	Direct Current	0.38%
60	Fundamental 1st order	100%
120	h2	0.16%
180	h3	0.77%
240	h4	0.04%
300	h5	0.57%
360	h6	0.04%
420	h7	0.25%
480	h8	0.01%
540	h9	0.06%
600	h10	0.02%
660	h11	0.03%
720	h12	0.01%
780	h13	0.05%
840	h14	0.00%
900	h15	0.03%
960	h16	0.01%

Total harmonic distortion is well below the acceptable range. The magnitude is 2.87%. Actually it may vary depending on the pureness of the grid power. From the above data while taking the 1st order harmonics as 100%, a graphical representation can be drawn in Figure 6.10 to give an idea of the other orders of harmonics.

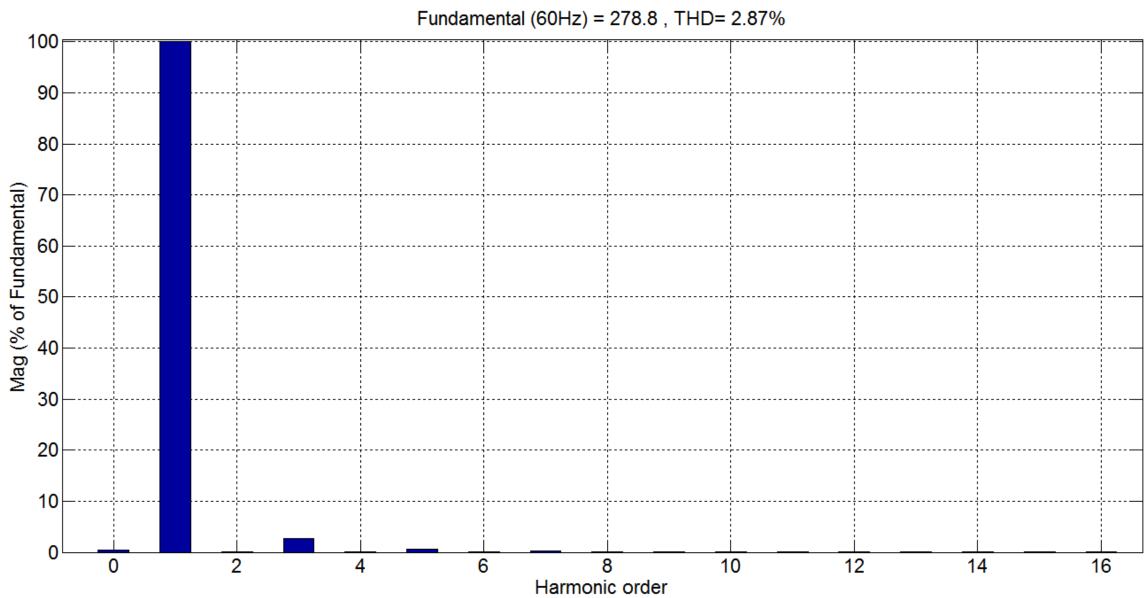

Fig 6.10: Harmonics of AC-DC converter while charging (Full view)

The output of the AC-DC converter needs to be chopped in order to go the battery. Battery has the ability to take maximum of 120 V DC voltage. In order to make the voltage to 120 V, the DC-DC converter, shown in Figure 4.3, the voltage has been reduced. In the Figure 6.11, the graph of the DC-DC converter has been shown. For the first 2 seconds the output voltage is not stable and that is why the voltage increases to 160 V and then starts reducing. The voltage reduces to 120 V just after 2 seconds and becomes stable enough and then continues to deliver 120 V DC to the battery.

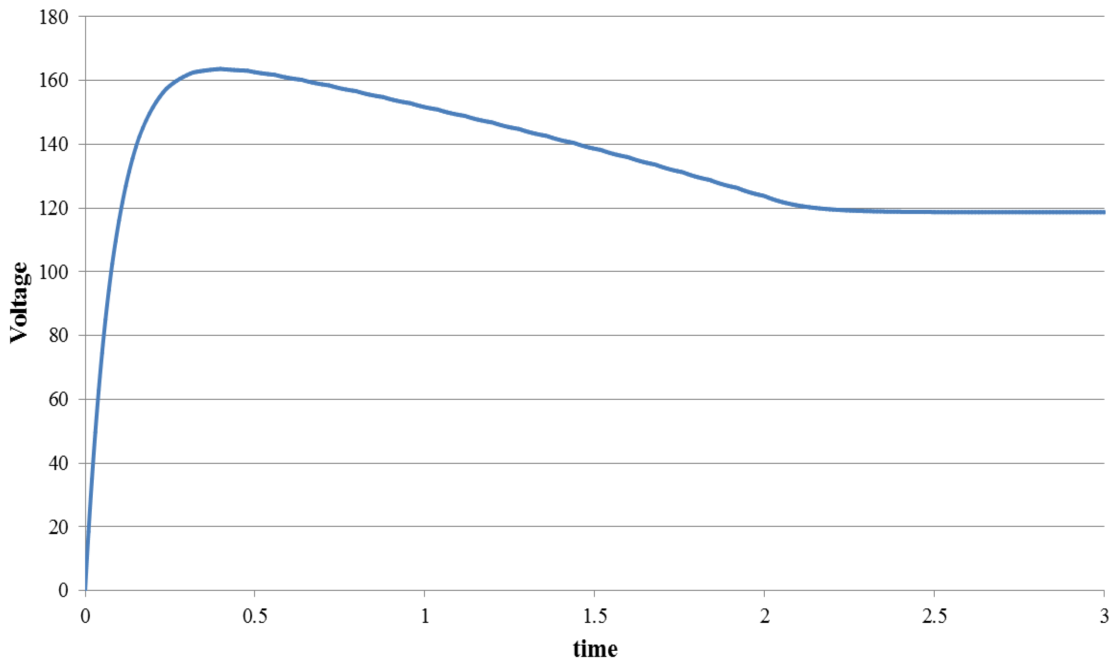

Fig 6.11: Output of DC-DC converter while charging (voltage)

The simulated output for the charging current comes to 10 A shown in Figure 6.12. From the research papers on vehicle to grid technology, it has been examined that the charging current ranges from 10 A to 35 A. The output of the design comes quite close to the average value. Actually, the amount of current injection is very high when a vehicle is plugged in for charging. In first couple of hours the battery takes around 80% of its charge. But after it reaches a certain point, battery starts tickle charging, a charging method which is very slow, a constant very low amount of current starts to inject to the battery until it reaches 100%. It happens to make the battery life longer, because with bulk or fast charging, there might have a chance to overcharge the battery. As a result it may reduce the lifetime of the battery.

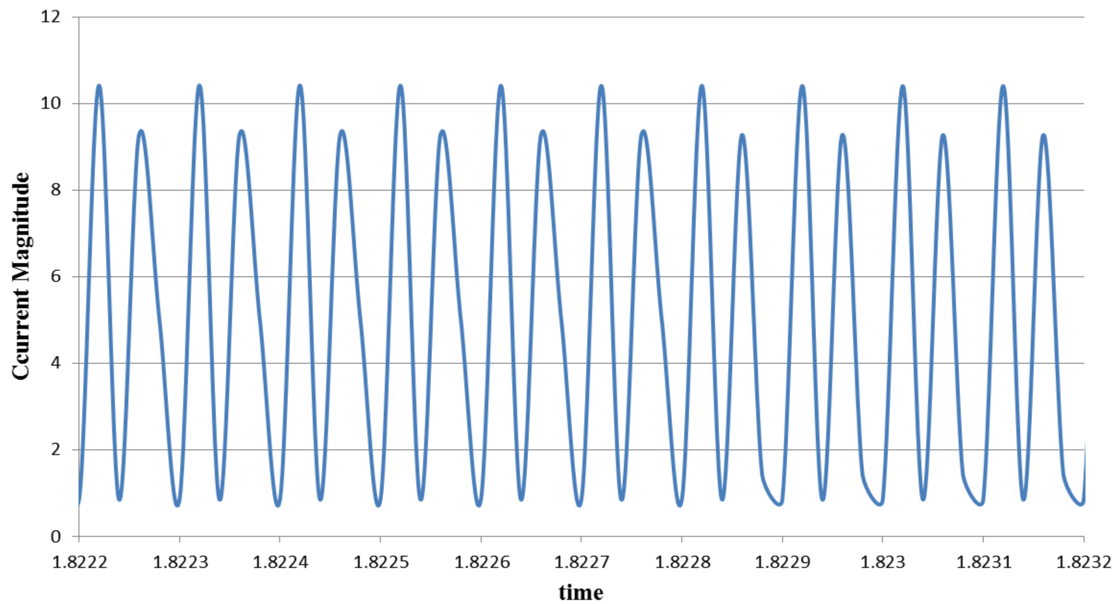

Fig 6.12: Output of DC-DC converter while charging (current)

6.3 RESULTS AND ANALYSIS

WHILE DISCHARGING:

- The output voltage of the DC-DC converter is 400 V. The output range may vary depending on the modulation index. But the range should be from 350V – 450V. And the output here is well below the maximum range of the standard output.

- The controller has set with a reference voltage of 380V. The voltage has set to 380V in order to match the output voltage with the grid voltage. The output of the DC-DC converter should follow the reference voltage and it is following the reference voltage starting from 0.5 seconds. This delay is not going to make any big difference because the total time for the integrated system which is connected to the grid is large enough compare to this 0.5 second.

- The output current is 65 A. Depending on the type of vehicle the magnitude of this current may vary from 30 A – 200 A. For plug-in hybrid vehicle the current is around 35 A, and for pure electric vehicle it may goes up to 200 A. That means the output current is in allowable range.

- The calculated output power delivered from the vehicle is =

$$120V \times 65A = 7.8kW$$

- The output voltage of the DC-AC converter is 170 V peak to peak. The grid voltage is 120 V rms is equal to 170 peak to peak. The voltage of the DC-AC converter matches with the grid voltage quite closely. The voltage match is necessary for uploading the power to the grid.

- The calculated power that goes to the grid is =

$$120V \times 65A \times \cos\theta$$

Here θ is the angle between the grid voltage and grid current. The value of $cos\theta$ ranges from -1 to +1. The amount of power that is going out of the grid may vary depending on the value of $cos\theta$. To get more amount of output power it is necessary to have the value of $cos\theta$ equivalent to +1.

+1 means the flow of real power and -1 means the flow of reactive power to the grid. Real power is the accepted power for the grid.

From the simulated design the power factor that has been got after 0.5 second is 0.93 on average. That calculates the power =

$$120V \times 65A \times 0.93 = 7.2kW$$

- The calculated efficiency for the system =

$$\frac{7.2kW}{7.8kW} \times 100 = 92.3\%$$

- Total Harmonics Distortion is 3.81%. The magnitude of the harmonics distortion should be less than 5% in order to make sure the good quality of power. If the distortion becomes large, that means the power that is going to flow to the grid have pollution in it. The power may flow to the grid, but that is not an acceptable format. It may harm the other components connected to the grid.

WHILE CHARGING:

- The magnitude of the output voltage of the AC-DC converter is 140 V. The range of this voltage may vary depending on the input grid voltage. The controller controls the voltage of this dc link. The maximum point is set to 380 V so that the increase of input voltage cannot exceed the maximum voltage level.

- The magnitude of the current that goes from grid side to the DC link is 278 V peak to peak. The current oscillates for first two seconds. After that the current starts becoming stable.

- The harmonics of the current that got from the simulation is 2.87% which is in the permissible range of total harmonics distortion.
- The calculated power that comes out from the grid to the battery side is =

  $$120V \times 300A \times \cos\theta$$

  When the power flows from grid side to the battery side the power factor got from the simulation is 0.98 on average. So the calculated power output becomes

  $$120V \times 300A \times 0.98 = 35.28kW$$

- The output voltage comes out of the DC-DC converter is 120 V. For the first 2 seconds the voltage oscillates and the maximum voltage goes up to 162 V. After 2 seconds the voltage becomes stable at 120V DC.
- The current that comes to the battery for charging the battery is 10 A DC current. The charging current varies depend on the charging system. For the first 75% - 80% state of charge of the battery, the battery goes with bulk charging. Bulk charging is very fast charging. But after its reaches saturation point, battery starts the tickle charging method. This charging method is very slow method. In this method a constant current with a very low magnitude comes to the battery for a long time. The low magnitude can be even less than 1A. This method provides battery a protection against overcharging.

- The maximum current for charging a battery in single phase outlet is 12 A for level 1 chargers according to Table 3.1. The current output of 10A is close enough for the single phase level 1 charger.
- The calculated power that goes to the battery from the grid is =

  $$120V \times 10A = 1200W = 1.2kW$$

  The total power that goes through the level 1 charger is around 1.44 kW. From the charger here total power of 1.2 kW is achievable which is quite close to the standard level 1 chargers.

CHAPTER 7

CONCLUSION AND FUTURE WORK

7.1 CONCLUSION

Different topologies of DC-DC converter and DC-AC converter had been studied for this research. Several issues such as harmonics distortion, less power factor, reactive power delivery, high number of switches etc. had been found on those topologies. The main problems in those topologies were those converters were not able to work as bi-directional converter. In order to make them work as bi-directional converters, the topologies had been modified.

Topologies for bi-directional DC-DC converter and bi-directional DC-AC converter had been integrated to make a bi-directional charger with the ability to deliver power back to the grid. A controller design had been proposed to control the charging current and voltage of the bi-directional converters. Several simulations had been done with MATLAB/Simulink to test those models and validate them.

To validate the results which have been got from the simulations, the simulated graphs and results had been compared with the results from other research and journal papers. The outcomes of the proposed model are as follows:

- The proposed model has a higher efficiency for delivering power from battery side to the grid side. Higher efficiency means more power will be delivered for a certain level of input power in a given amount of time. In case of power delivery higher efficiency is very much required.

- The proposed model has less harmonics distortion compare to other integrated systems. Less harmonics means the quality of the delivered power is better. Less harmonics distortion is necessary for this system to ensure that the delivered power will not pollute the grid.

- The model has a less number of switches which articulates less conduction loss. Less number of switches is better for any system since more switches leads the system to a heavier and bulkier system.

7.2 CONTRIBUTIONS OF THIS RESEARCH

The contributions of this research are as follows:

- Establish a design by integrating two different types of bi-directional converters.

- Modify and integrate a controller system to control the charging current and voltage of the converters.

7.3 FUTURE WORK

There are a lot of areas where future studies can be done. The work that is documented in this paper can be further progressed as following:

- State of Charge (SOC) of the battery was not taken into account while modeling and simulations had been done.

- State of charge (SOC) of the battery can be modeled and combined with the system. In that way the battery can be handled more efficiently for grid integration.

- Experimental setup with a real battery pack from EV or PHEV would be given more accurate results. Real battery pack can behave much more differently in certain temperature and weather condition.

- Only real power has taken into consideration for the model. Reactive power can be present as well in the system. Research can be done to compensate the reactive power.

- Connect the battery pack more frequently with the grid for uploading power to the grid and pull it out may cause reduction in the battery life. So, an algorithm can be derived and new battery model can be proposed to reduce the risk of battery life.

APPENDIX

The value of the parameters used for the bi-directional DC-DC converters are given in the table A.1:

S_5, S_6, S_7, S_8	IGBT switches
f	25 kHz
L_o	608 µH
V_{batt}	120 V
C_o	470 µF

The value of the parameters used for the DC-DC controllers are given in the table A.2:

Buck	
K_i	1
K_p	0.001
PWM frequency f_{PWM}	50 kHz
Boost	
K_i	0.5
K_p	0.001
PWM frequency f_{PWM}	50 kHz

The parameters used for the bi-directional AC-DC converters are given in the table A.3:

S_1, S_2, S_3, S_4	IGBT switches
f	25 kHz
L_C	7.6 mH
V_{grid}	120 V, 1-phase AC
C_{dc}	500 µF

The parameters used for the AC-DC controllers are given in the table A.4:

1st PI Controller	
K_i	2
K_p	0.1
f	20 kHz
2nd PI Controller	
K_i	2
K_p	0.85
f	20 kHz

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